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ELECTROMAGNETIC SHIELDING OF STRUCTURAL FOAMS BY USING INTERNAL CONDUCTIVE MATERIALS

AUGUST 1979

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Engineering Experiment Station
Atlanta, Georgia

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by

D. G. Bodnar and B. M. Jenkins

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This work was performed under contract DAAG46-77-C-0027 for the Army Materials and Mechanics Research Center, Watertown, Massachusetts. The contract monitor for the Army was Alan M. Litman, Organic Materials Laboratory, Composites Division.

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I. INTRODUCTION

A. Purpose of Study

The principal objective of the program was to assess the ability to achieve RF shielding by adding conductive materials internally to structural foams. The primary conductive material of interest was carbon/graphite fibers although consideration was given to metalized glass fibers and to conductive metal particles. The ultimate goal of the analysis is to provide design input for fabrication of radio set housings made from structural foams.

This report covers work performed under both phases of the contract. During the first phase a review was performed of the applicability of several analysis techniques to shielding calculations for structural foam that is internally loaded with conductive materials. Data were compiled that permitted a selection of sample panels to be built for testing during the second phase of the program. These panels were supplied by the Army Materials and Mechanics Research Center (AMMRC) and were tested by the Engineering Experiment Station (EES) at the Georgia Institute of Technology. Measured shielding effectiveness is presented versus frequency for several different materials.

B. Background

There is an increasing tendency among producers of both military and civilian electronics equipment to use plastic housings for the electronic equipment. The trend to replace cast or fabricated metal housings with plastics has been driven by the desire to obtain light weight, corrosion resistance, parts consolidation, and other economic benefits. The tendency to replace metal housings with plastic housings has a very pronounced effect on the ability of the housing to shield electromagnetic energy from leaving or entering the structure. Plastics, being good insulators, are therefore highly transparent to electromagnetic radiation.

The basic technique for improving the RF shielding ability of plastic housings is to reintroduce the shield into the plastic. This is done by making the plastic electrically conductive so that it will reflect and/or absorb electromagnetic energy. To accomplish this, a layer of conductive material can be applied to the surface of the casing. The conductive layer may take the form of metal foil, tape or screening, plating, vacuum metallizations, metal spraying or conductive coatings. Each of these methods involves a separate manufacturing process and some are not readily applicable to complex shapes. Many of these techniques have been tried in industry and found effective for different applications. However, under a military environment (extremes of temperature and humidity), the above mentioned shielding methods may not be adequate. For example coatings may scratch, chip or flake off under military use.

A technique which has not been used and which is the subject of the study reported herein is to reinforce the plastic with carbon/graphite fibers, metal coated glass fibers, or metallic powders. These particles are not all in electrical contact with one another and so they are expected to have somewhat different shielding characteristics than those obtained by coating or lay-up purposes. The advantages of this method of shielding are that both molding and shielding are performed in one operation (eliminating an expensive secondary operation) and the shielding medium is incorporated throughout the molded item (not just on the surface).

II. THEORETICAL CALCULATIONS

This section summarizes some of the theoretical analyses performed during the study. The emphasis herein is directed toward obtaining trends in shielding performance based on changes in material characteristics. Several mathematical analysis techniques are reviewed for assessing shielding effectiveness. Included are the method of moments, wire grid analysis, meteorological models, and plane wave analysis. Calculations are presented of shielding effectiveness in the HF through UHF frequency range for various material characteristics.

A review of mathematical analysis techniques was an essential part of the program because of the complicated nature of the shielding structure. Specifically, it is anticipated that the conducting particles will be essentially randomly distributed throughout the structural foam due to the manufacturing process. The density (number of particles per unit volume) of conducting particles can be varied over a wide range of values by simple changes in the manufacturing process. In addition, the frequency range of interest is large, covering HF through UHF frequencies (roughly 1-1000 MHz). Finally, the material parameters may vary greatly from moderately conducting carbon/graphite fibers, to highly conducting metal powders, to magnetic powders. This wide range of parameters creates a difficult electromagnetic analysis problem. The next several subsections discuss some of the analysis techniques that were considered. A plane wave analysis technique was selected as the most applicable one.

A. Plane Wave Analysis

The analysis of Section IIC shows that a large number of contacting fibers is required in a panel to provide a reasonable amount of shielding. Since the fibers themselves and the fiber contacts are lossy and since there is a large number of fibers, one might expect that a lossy conductor model would adequately describe a fiber loaded panel. Consequently, an analysis was performed of the panels representing them as lossy conductors and using a plane wave as the field incident on the panel. For HF frequencies and above, it is usually necessary to consider only plane wave fields and not near magnetic and electric fields in addition because the shield is usually electrically far enough away from the source of energy. Plane waves arise naturally in electromagnetic (EM) analysis since plane wave functions form a complete set of functions for representing RF fields. Thus, any arbitrary EM field can be represented by a sum of properly weighted plane wave functions. In addition, RF fields behave locally as plane waves at large distances from a spacially finite source of RF energy. Thus, RF fields impinging on shields can often be represented by plane waves. Only normal incidence is considered since it indicates major trends in the data.

An evaluation of the shielding effectiveness of a panel can be performed by modeling the panel as an infinite plane as shown in Figure 1. To simplify the mathematics, the panel is represented as a homogeneous material having a permeability μ_o, a permittivity of $\varepsilon = \varepsilon_r \varepsilon_o$, and a conductivity σ where μ_o and ε_o are the free space permeability and permittivity, respectively, and ε_r is the dielectric constant of the panel. Next the incident RF field is approximated by a plane wave impinging on the panel at normal incidence. A portion of the incident wave is reflected by the panel due to the change in electrical properties it exhibits to the wave. The remainder of the wave enters the panel, is attenuated by the lossy material in the panel, and a portion of this energy exits the panel into Region 3. Multiple reflections inside the panel must be properly accounted for in the analysis.

The equations describing the transmission of plane waves through a plane sheet of lossy material at normal incidence may be formulated as follows. The electric field intensity in Region 1 consists of an incident and a reflected field which may be written, respectively, as

$$E_i = E_0 e^{jk_1 z - j\omega t}$$

$$E_r = E_1 e^{-jk_1 z - j\omega t}$$

In Region 2, the field must be expressed in terms of positive and negative waves as

$$E_s = (E_2^+ \, e^{jk_2 z} + E_2^- \, e^{-jk_2 z}) e^{-j\omega t}$$

while the transmitted field in Region 3 is

$$E_t = E_3 e^{jk_3 z - j\omega t}.$$

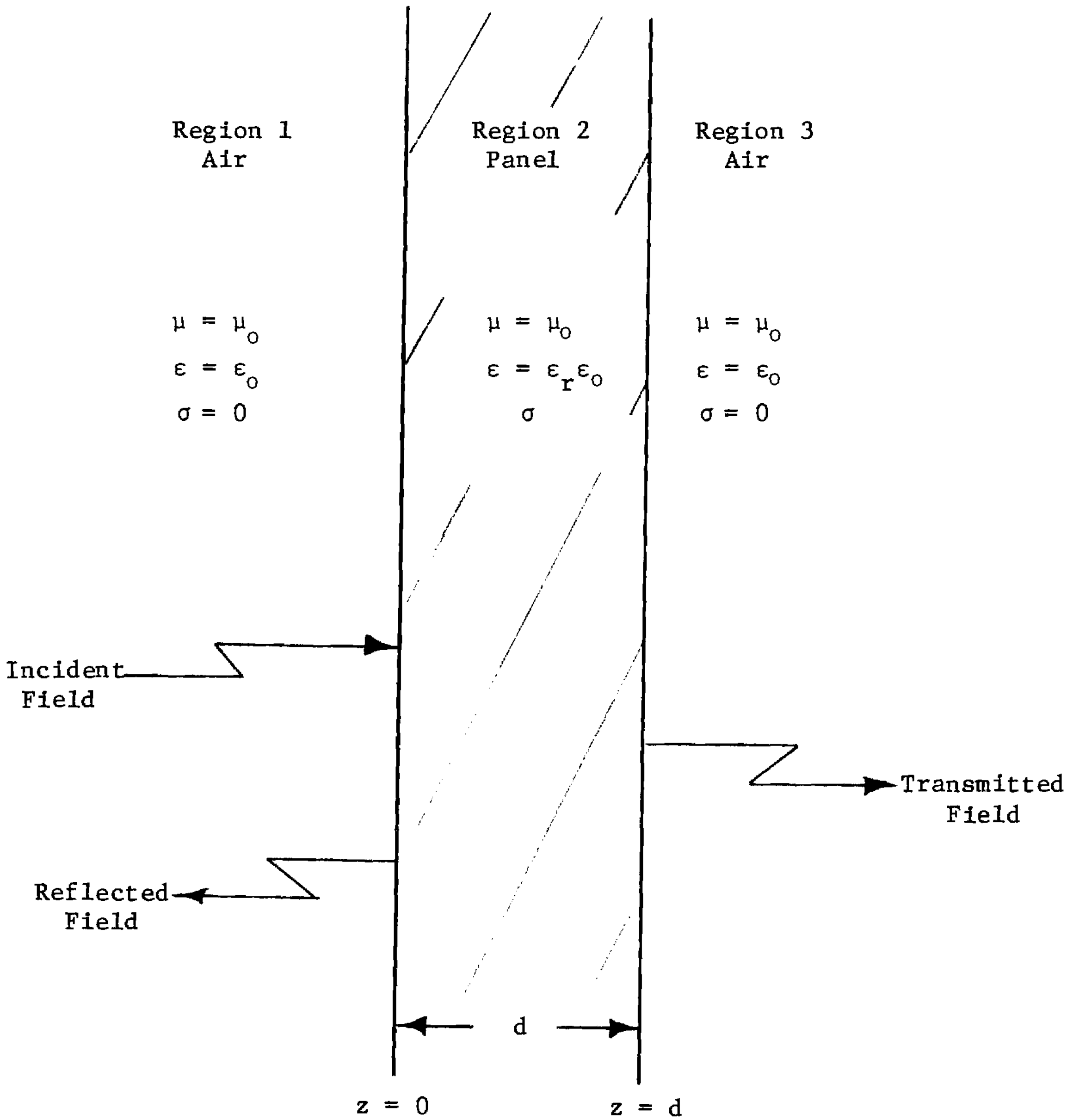


Figure 1. Model Used in Plane Wave Analysis of Shielding Effectiveness of Panels

The quantities E_0, E_1, E_2^+, E_2^-, and E_3 are complex constants representing the complex amplitudes of the waves. It is assumed that the incident field E_0 is known and that the transmitted field E_3 is to be found. The quantity k_i ($i = 1,2,3$) represents the propagation constant or wave number of the wave in region i. The frequency f of the wave is related to the angular frequency ω by $\omega = 2\pi f$.

The magnetic field intensity H in each region can be determined from Maxwell's equations and will be functions of E_0, E_1, E_2^+, E_2^- and E_3. Matching the tangential E and H fields at the two boundaries of the sheet produces 4 equations in the 4 unknowns E_1, E_2^+, E_2^- and E_3 (recall that E_0 is assumed known). Solving these equations, one can obtain the power transmission coefficient

$$T = \frac{(\sin^2\delta_{12} + \sinh^2 s_{12})e^{\beta_1 d}}{\sin^2(\alpha_2 d + \delta_{12}) + \sinh^2(\beta_2 d + s_{12})} \tag{1}$$

where

$$T = \left|\frac{E_3}{E_0}\right|^2$$

$$\alpha_i = \omega\left[\frac{\mu_i \varepsilon_i}{2}\left(\sqrt{1 + \frac{\sigma_i^2}{\varepsilon_i^2\omega^2}} + 1\right)\right]^{1/2} \qquad i = 1,2$$

$$\beta_i = \omega\left[\frac{\mu_i \varepsilon_i}{2}\left(\sqrt{1 + \frac{\sigma_i^2}{\varepsilon_i^2\omega^2}} - 1\right)\right]^{1/2} \qquad i = 1,2$$

$$s_{12} = -\frac{1}{2}\ln R_{12}$$

$$R_{12} = \frac{(\mu_2\alpha_1 - \mu_1\alpha_2)^2 + (\mu_2\beta_1 - \mu_1\beta_2)^2}{(\mu_2\alpha_1 + \mu_1\alpha_2)^2 + (\mu_2\beta_1 + \mu_1\beta_2)^2}$$

$$\tan\delta_{12} = \frac{2\mu_1\mu_2(\alpha_2\beta_1 - \alpha_1\beta_2)}{\mu_2^2(\alpha_1^2 + \beta_1^2) - \mu_1^2(\alpha_2^2 + \beta_2^2)}$$

The quantity T represents the shielding effectiveness of the panel since it equals the ratio of the power transmitted through the panel to the power incident on the panel. Equation 1 was evaluated numerically and compared with data in the literature, and the agreement has been very good. These and other checks indicate that the formula is accurate.

Figures 2 and 3 present the results of some of the data obtained using Equation 1. Figure 2 shows the shielding effectiveness of various 9 mm thick panels versus frequency. A panel thickness of 9 mm was selected since it is nearly equal to 0.36 inches which is the thickness of the preliminary panels supplied by AMMRC. The curves in Figure 2 are for conductivities between 1 and 10,000 Siemens/meter. Increasing the conductivity of the panel increases its shielding effectiveness as expected. For each value of conductivity, the shielding effectiveness of the panel was calculated for three values of dielectric constant for the panel, namely 1, 4, and 16. In all cases the permeability of the panel was assumed to be equal to that of free space which is usually true for non-magnetic materials. Varying the dielectric constant between 1, 4 and 16, produced such small changes in shielding effectiveness that they were imperceptible when plotted on a graph. Thus the curves in Figure 2 apply for any value of dielectric constant for the panel up to 16. The dielectric constant of typical matrix material used in the panels is about 4 in an unfoamed state. Presumably it is less in a foamed state. Thus, Figure 2 applies to the panels of interest. The lack of dependence of the curves on dielectric constant is important since it says that the matrix material used in the panel has very little effect on shielding effectiveness as long as the conductivity of the panel is greater than 1 Siemen/meter. Thus the conductive properties of the array of fibers in the panel determines the shielding properties and not the matrix material. Figure 2 shows that a conductivity of about 300 S/m or greater must be achieved in the panel to obtain 50 dB or more of shielding effectiveness. Shielding effectiveness of at least 50 dB is typically required for military equipment.

Figure 3 is a plot of shielding effectiveness versus panel thickness with frequency and panel conductivity as parameters. Again as with Figure 2, the curves in Figure 3 do not change when the dielectric constant of the panel is varied from 1 to 16. Typical panel thickness of interest varies between 1/4 and 3/8 inches (roughly 6 to 10 mm) according to AMMRC. Figure 3 shows that a conductivity of about 400 will be required for 6 mm thick panels at 10 MHz to obtain 50 dB of shielding effectiveness. For a $\sigma = 100$ S/m panel, increasing the panel thickness from 6 to 10 mm increases the shielding effectiveness by 4 dB at 10 MHz, by 7 dB at 100 MHz and by 22 dB at 1000 MHz. Figure 3 shows that increasing conductivity rather than increasing panel thickness is more effective for obtaining 50 dB of shielding

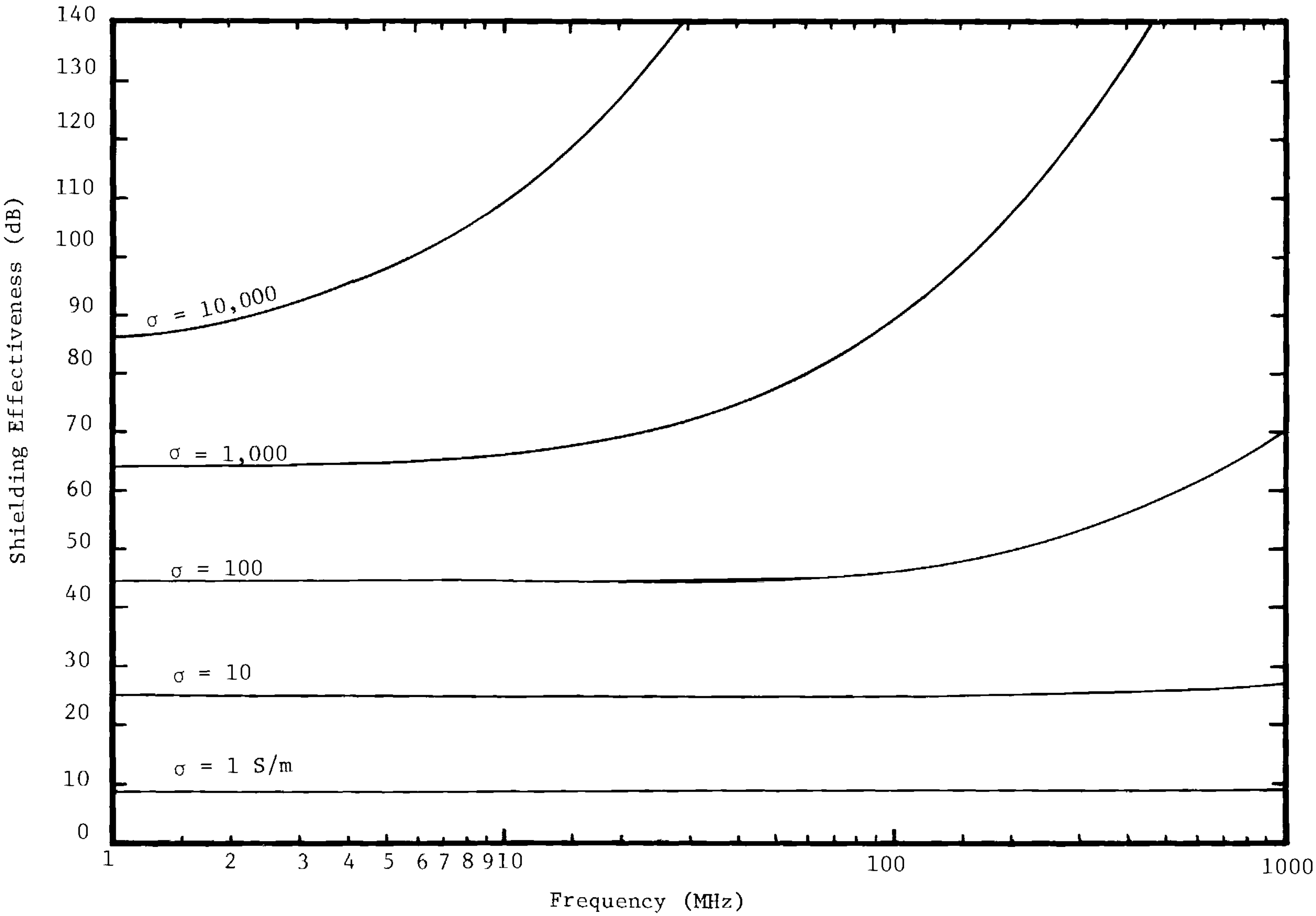


Figure 2. Plane Wave Shielding Effectiveness of 9 mm Thick Planar Panels versus Frequency

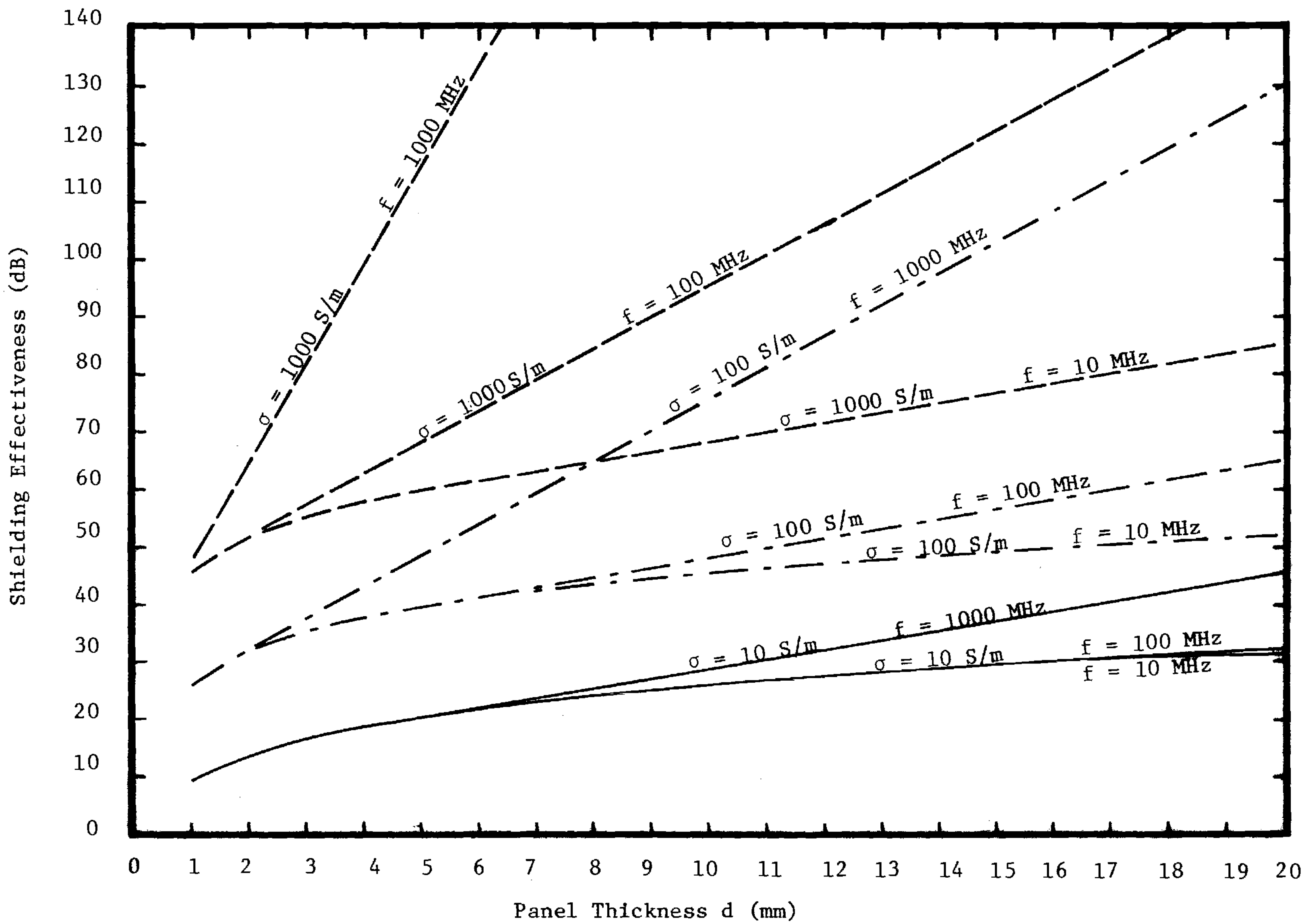


Figure 3. Plane Wave Shielding Effectiveness of Planar Panels versus Thickness

effectiveness at HF and VHF frequencies for the range of panel thicknesses that are of interest.

The principal difficulty with the plane wave analysis comes in assigning an effective conductivity to the network of particles in the foam. As discussed in Section IIE, an exact calculation of the conductivity of the panel appears impossible. Attempts are still being made at an approximate analysis. Section IIIB presents some measurements of the conductivity of several panels supplied by AMMRC. As discussed in that section, the predicted shielding effectiveness based on the measured conductivity and on Figure 2 agrees well with measured values of shielding effectiveness given in Section IIIA. The conductivity measurements of Section IIIB showed a maximum value of about 30 S/m for the current AMMRC panels. Figure 2 shows that the conductivity of the panel must be increased by about one order of magnitude in order to obtain 50 dB or more of shielding. Materials that should produce such conductivity are discussed in Sections IIE and IIF.

B. Moment Method Analysis

A very powerful technique for analyzing electromagnetic problems is the moment method [1] first formulated by Harrington. It can in principle analyze a wide variety of conductor geometries, including arbitrarily oriented conductors and lossy conductors. Because of its ability to handle a wide range of parameters, the moment method was given careful consideration for the shielding effectiveness analysis of this program. Some of the features of moment method analysis will be discussed first followed by applications for the problem at hand.

The moment method formulates the problem of interest in terms of an operator equation of the form

$$L(f) = g \tag{2}$$

where L is a known operator, g is a known function and f is the unknown function that is to be determined. The unknown function f is expanded in terms of a known set of basis functions $\{\phi_n\}$ with unknown coefficients $\{C_n\}$ such that

$$f = \sum_n C_n \phi_n . \tag{3}$$

A set of known testing functions $\{w_m\}$ is then used to test (2) after (3) is substituted into (2). This operation yields

$$\sum_n C_n < w_m, L(\phi_n) > \; = \; < w_m, g > \tag{4}$$

where <> stands for the inner product and the linearity of the operator L has been used in obtaining (4). The advantage of the formulation used in (4) is that the operator equation for the unknown function f has been replaced by a matrix equation for the unknown constants $\{C_n\}$. Let N functions be used in (3) to represent f. If (4) is performed for each of N different testing functions $\{w_m\}$, then (4) represents N equations in N unknowns. Standard matrix techniques can be used to solve this system of equations for the unknowns $\{C_n\}$.

A great deal of work has been done on applying moment method techniques to wire antennas [2]. Carbon fibers are short, lossy wires and so can be analyzed by these wire antenna, moment method techniques. The operator equation corresponding to (1) for a single wire is a Fredholm integral equation of the first kind and is given by [2]

$$E_z^i(z) = \int_{-L/2}^{L/2} K(z,z')I(z')dz' \tag{5}$$

$E_z^i(z)$ is the component of the known incident electric field tangent to the wire, $K(z,z')$ is the known kernel of the equation, and $I(z')$ is the unknown current at point z' on the wire. The incident field can be specified for the electromagnetic problem of interest and can be a plane wave, an electric near field, or a magnetic near field. Knowing E and K in (5), one can solve for I by representing it as a sum of known functions with unknown coefficients as in (3) and then forming the inner product as in (4).

A large number of wires instead of a single wire is of interest for the loaded structural foam problem. The moment method can also be used to analyze a conducting body consisting of multiple wires. The current in each wire is expanded in a known functional form with an unknown amplitude. These unknown amplitudes are determined using matrix techniques via the moment method. The number of wires that can be analyzed by such a technique is conceptually unlimited. In practice, however, the number of wires (actually the total number of expansion functions) that can be treated is limited to 300 to 500 due to computer storage, round-off, and speed limitations.

The carbon fibers in the foam form a dense chaff-like cloud which tends to scatter incident energy back to the source and let little energy through the cloud. A report by Garbacz [3] discusses the application of moment method techniques to chaff clouds. A cloud of resonant (half wavelength) dipoles illuminated by a plane wave source is analyzed. Galerkin's method is used in which the testing and basis functions are identical. Each dipole is conceptually split into two segments and the current on each segment is represented by a piecewise sinusoidal current of unknown amplitude and phase. The coupling (i.e., mutual impedance) between each segment of current and any other segment (or itself) can be expressed in the form of a reaction integral (i.e., an inner product integral) based on the reaction matching technique of Richmond [4]. The significant fact which makes the reaction matching technique attractive is that all the reaction integrals may be evaluated in closed form, thereby permitting the rapid determination of all elements in the impedance matrix. Garbacz says that the largest chaff cloud that they can handle consists of 250 chaff elements due to computer storage limitations. This limitation is consistent with results obtained by Georgia Tech and others. Typical spacings between dipoles was $\lambda/2$ or greater (λ = free space wavelength) for the Garbacz work. He states that his results become unreliable when the average inter-element spacing is $\lambda/8$ or smaller. More than two current segments per dipole are then required to accurately represent the current in the presence of strong mutual coupling between the chaff elements. Increasing the number of current segments per wire decreases the number of chaff elements that can be analyzed. For example, a 200 dipole cloud can be solved with two-segment models while only a 22 dipole cloud can be solved using a four-segment model, according to Garbacz.

According to AMMRC, the carbon fibers typically used in the foam panels to date have been 1/8 to 1/16 inch long. Since λ = 11,800 inches at 1 MHz and λ = 11.8 inches at 1 GHz, typical fiber lengths of interest vary from $\lambda/(1.9 \times 10^5)$ to $\lambda/94$. Since these fiber lengths are orders of magnitude smaller than those used by Garbacz, it might be possible that a one-segment current model might be usable even though the fibers are very close together. Thus, the moment method could be used as long as total number of fibers in a panel was small enough. A formulation different from Garbacz's would, of course, have to be used.

Measurements made on typical panels loaded with carbon/graphite fibers gave a relatively low DC resistance indicating that a substantial number of fibers are in electrical contact. This situation is desirable for providing good shielding. However, it complicates the analysis since it suggests that a large number of fibers is present in a panel. Some simple calculations were performed to determine if the number of fiber segments in a typical panel was consistent with that which the method of moments can handle. Typical structural foam panels may contain 30 to 40% fibers by weight and have a 20% density reduction due to air in the panel. The density of the plastic in the panel is $\rho_p = 1.1$ to $1.2\ g/m^3$ while that of the fibers is $\rho_f = 1.8\ g/cm^3$. The fibers are typically 1/16 inch long and 10 μm in diameter. A typical AMMRC panel is 7.94 inches on a side, 0.25 inches thick and weighed approximately 200 grams. An estimate of the number of fibers in the panel was made based on these values. The total weight W_f of the fibers in the panel is 80 grams assuming that the panel is 40% fibers by weight. The number N_f of fibers in the panel is given in terms of the diameter D_f and the length L_f of the individual fibers as

$$N_f = \frac{4W_f}{\pi D_f^2 L_f \rho_f} .$$

Using the above values $N_f = 3.6 \times 10^8$ or 1.4×10^6 fibers per cubic centimeter are present in the panel. The method of moments, however, cannot handle this number of fibers. It could handle a cube a few hundredths of a centimeter on a side but this volume is too small compared to the wavelength of operation to provide useful information.

Several workers in the area of moment method techniques were contacted to see if the technique could be used to analyze a large number of contacting wires. The impression obtained from these discussions is that although some improvements could be made over conventional moment method approaches, the improvements would not be substantial enough to solve the problem at hand.

Due to the above consideration, alternate analysis techniques were pursued. One approach that was examined is to treat the panel as a lossy dielectric material (see Section IIA). This model seems reasonable due to the relatively large number of contacting fibers present in the panel.

Plane wave reflection and transmission coefficients can be obtained to investigate the shielding properties of the panel based on this model. A cruder model which will be presented next is obtained by using a periodic wire grid to model the array of fibers.

C. Wire Grid Model

It is instructive to examine several electromagnetic scattering geometries in order to determine some of the dominant characteristics of conductively impregnated structural foam. The first question that will be examined is how closely the internal fibers must be in order to provide effective shielding. This problem will be addressed first by approximating the fibers as an array of infinitely long, identical, parallel, perfectly conducting wires as shown in Figure 4. Although this is a very crude model it is useful in illustrating an important point. Let the wires have a diameter, D, and a spacing, S, and let a plane wave having a wavelength, λ, be incident normal to the grid. The incident electric field may be polarized either parallel (i.e., $E_{||}$) or perpendicular (i.e., $E_{\perp}$) to the axis of the wires. The equivalent circuit of the grid as seen by the incident wave is given by Marcavitz [5] and is shown in Figure 5. When $S/\lambda<<1$ the circuit parameters are:

$$\frac{X_a}{Z_o} = \frac{S}{\lambda} \left[\ln\left(\frac{S}{\pi D}\right) + 0.601\left(\frac{S}{\lambda}\right)^2\right] \tag{6}$$

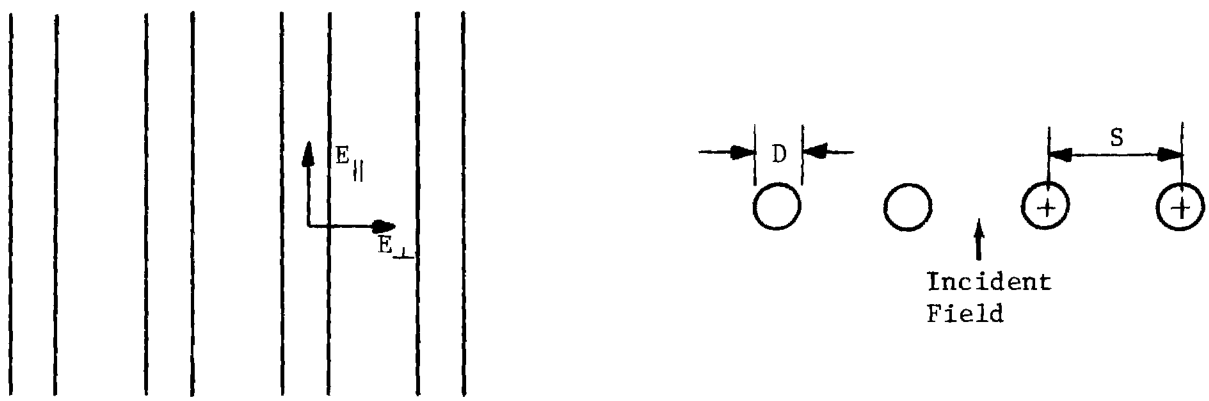
$$\frac{X_b}{Z_o} = \frac{S}{\lambda} \left(\frac{\pi D}{S}\right)^2 \tag{7}$$

$$\frac{B_a}{Y_o} = \frac{S}{2\lambda} \left(\frac{\pi D}{S}\right)^2 \frac{1}{A_2} \tag{8}$$

$$\frac{B_b}{Y_o} = \frac{2\lambda}{S} \left(\frac{S}{\pi D}\right)^2 A_1 - \left(\frac{S}{4\lambda}\right)\left(\frac{\pi D}{S}\right)^2 \frac{1}{A_2} \tag{9}$$

where

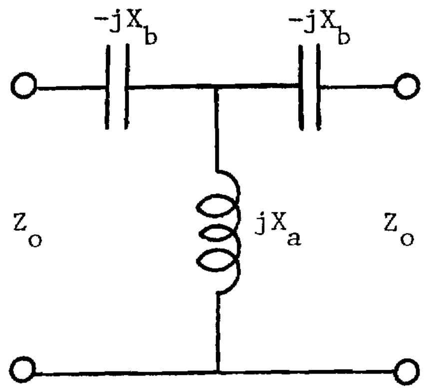
$$A_1 = 1 + \frac{1}{2} \left(\frac{\pi D}{\lambda}\right)^2 \left(\ln \frac{S}{\pi D} + \frac{3}{4}\right)$$



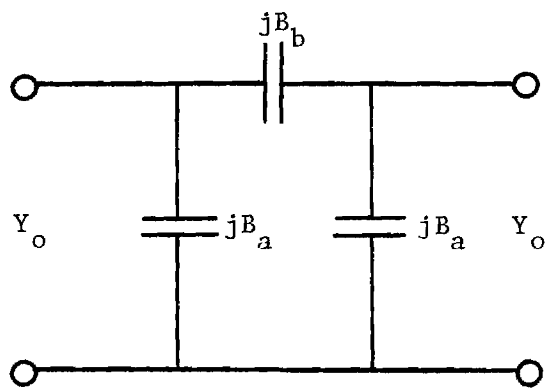
(a) Front View

(b) Top View

Figure 4. Wire Grid Approximation of Structural Foam Filled with Fibers



(a) For Parallel Polarization



(b) For Perpendicular Polarization

Figure 5. Equivalent Circuit of Wire Grid at Normal Incidence

$$A_2 = 1 + \frac{1}{2} \left(\frac{\pi D}{\lambda}\right)^2 \left[\frac{11}{4} - \ln \frac{S}{\pi D}\right] + \frac{1}{24\pi} \left(\frac{\pi D}{S}\right)^2$$

and Z_o and Y_o are the characteristic impedance and admittance of free space, respectively.

An inspection of (6) and (7) reveals that X_a and X_b approach zero as λ becomes large. Thus, the inductor in Figure 5a shorts the transmission line at low frequencies and little power is transferred to the opposite side of the grid. Thus, the grid acts as an effective shield to parallel polarization at low frequencies. An inspection of (8) and (9) reveals that B_a approaches zero and that B_b becomes large as λ gets large. Thus, the shunt capacitors in Figure 5b act as open circuits and the series capacitor acts as a short as λ gets large. This situation indicates that a large amount of energy travels past the grid and that the grid is not an effective shield for perpendicular polarization.

The amount of power passing through the grid is plotted in Figure 6. The power transmission coefficient, T, is plotted in this figure and is the ratio of the power passing through the grid to the power incident on the grid in decibels. Figure 6 indicates, for example, a transmission loss of 40 dB for parallel polarization and only 0.001 dB for perpendicular polarization when $S/\lambda = 0.038$ and $D/S = 0.28$.

The question now arises as to whether the good shielding characteristics for parallel polarization are the result of the wires simply being longer in the axial direction or is it the fact that the wires are infinitely long in that direction. What would the shielding characteristics be if one replaces the infinitely long wires of Figure 4 with a two dimensional array of short wires? It turns out that the shielding characteristics are bad for both polarizations as will be shown next. The conclusion to be drawn from all of this is that a large number of noncontacting fibers does not provide effective shielding. Only by having long conductive paths can good shielding be obtained.

A model for the fibers consisting of short, noncontacting plates is shown in Figure 7. This is a more realistic model than that of Figure 4. The model in Figure 7 consists of a doubly-periodic array of thin rectangular plates. Analysis of such structures has been performed by Chen [6] and by Montgomery [7]. Chen analyzes an infinite array of thin plates arranged in a doubly-periodic grid and analyzes the fields in terms of a set of Floquet mode functions. For an arbitrarily polarized plane wave incident from an

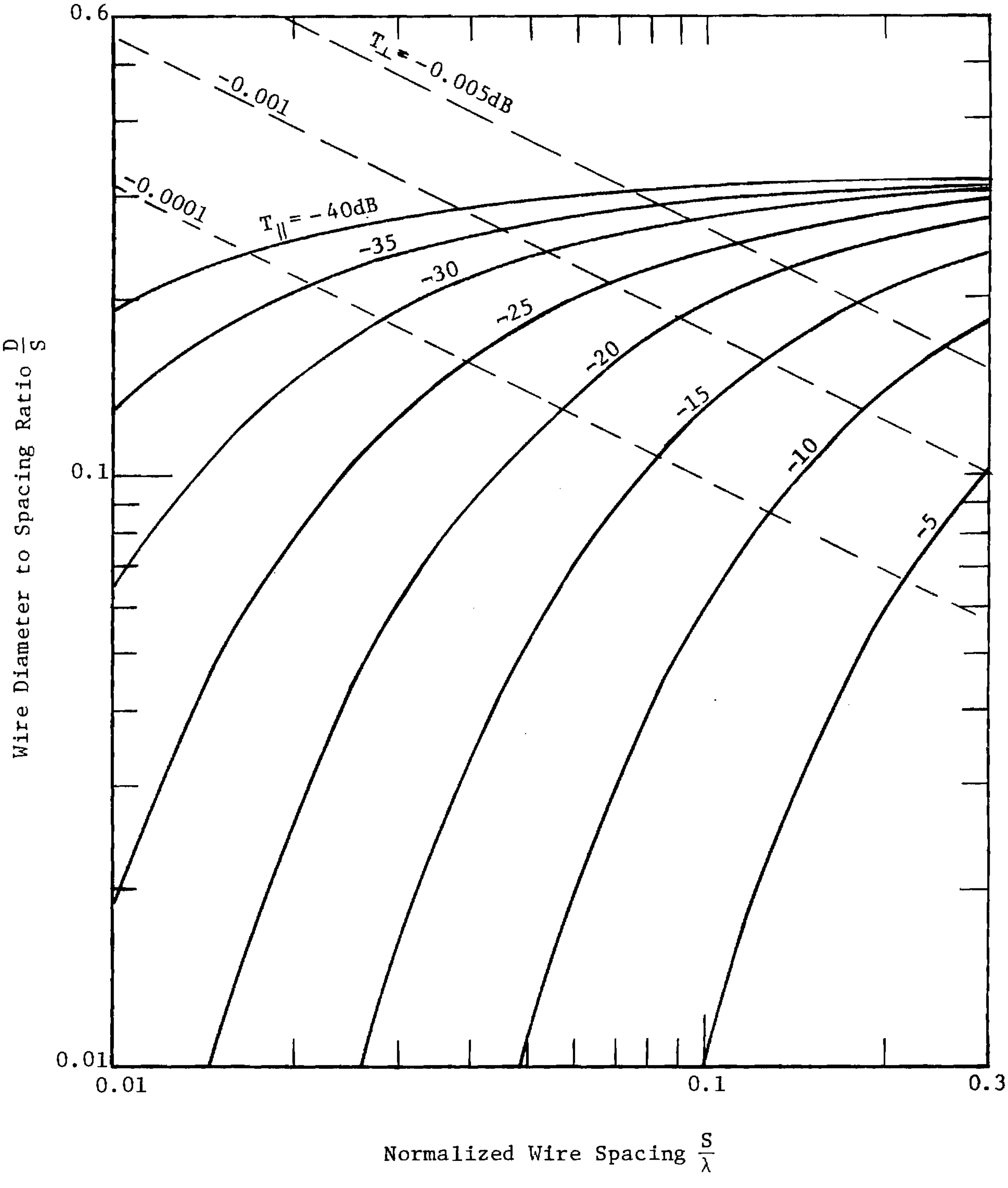


Figure 6. Transmission Coefficient for Parallel Polarization and for Perpendicular Polarization for a Grid of Round Wires

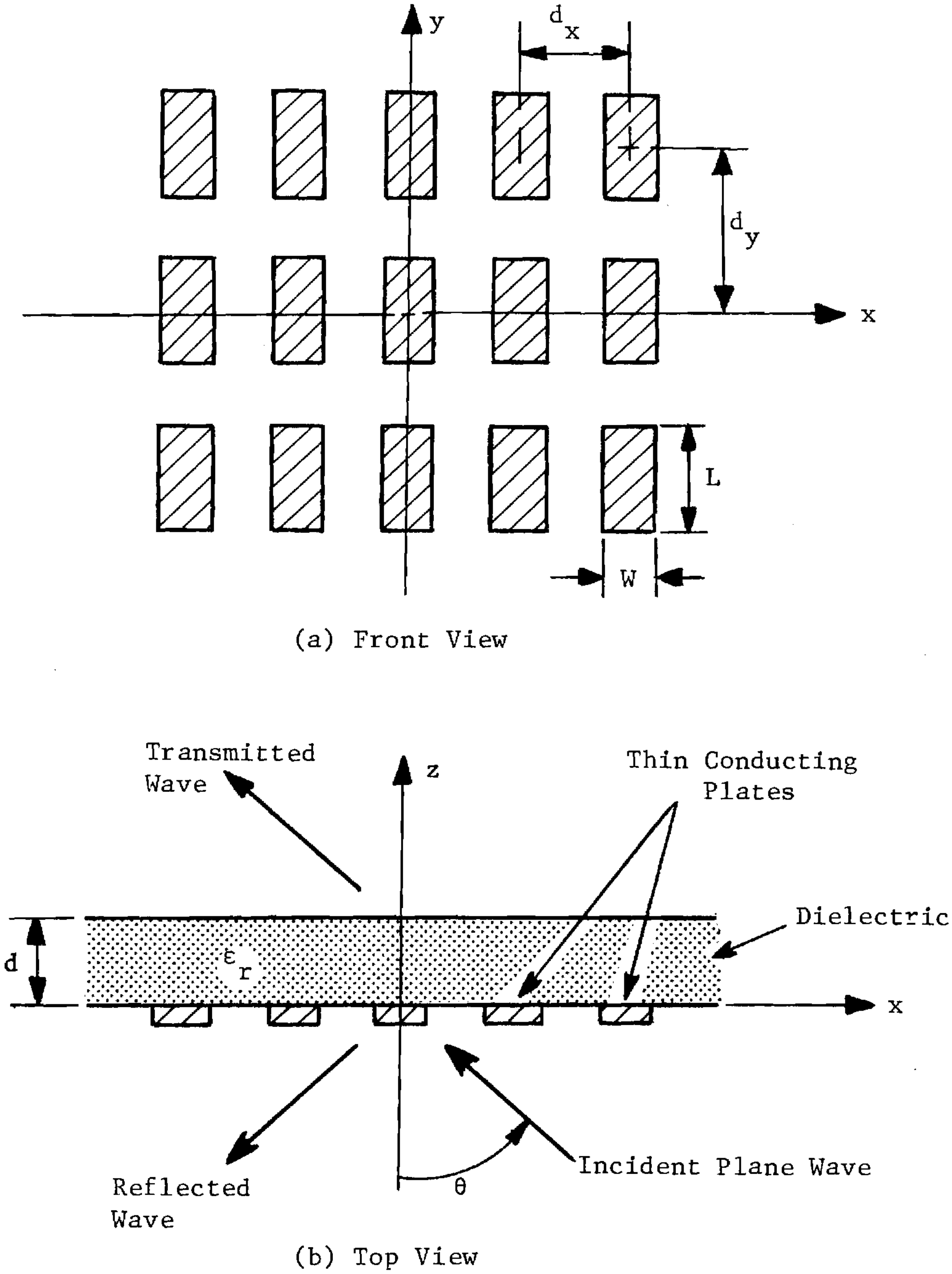


Figure 7. Model Consisting of an Infinite Periodic Array of Thin Conducting Plates on a Dielectric Sheet

oblique angle, he obtains the current on the plate using moment method techniques. From this current he calculates the near-field distribution, the distant reflected wave as well as the reflection coefficient from the structure. Montgomery treats the same problem of a doubly-periodic array of thin conductors, but on a dielectric sheet. He also uses Floquet modes for representing the field and obtains via moment methods a system of equations for solving for the same type of field quantities that Chen considered.

Both Chen and Montgomery provide general equations for analyzing their respective problems. These equations must be programmed for a digital computer to obtain numerical results. Sample calculations are presented by both authors, but no general design information is presented. However, there is a trend in Chen's data that is useful. Chen presents data for strips that are from 1.27 to 1.35 cm long, are 0.127 to 0.508 cm wide, and are spaced from 0.76 to 2.54 cm apart. His data shows that 100% of the incident power is reflected (i.e., maximum shielding) near 10 to 11 GHz and that the amount of reflected power decreases rapidly with frequency. Only from 5 to 30% of the power is reflected at 8 GHz. Thus, these arrays provide less than 1.6 dB of shielding at 8 GHz. Chen presents data only as low as 6 GHz, but his data shows the amount of reflected power monotonically decreasing as the frequency of the incident wave decreases.

One should expect the amount of scattered power to decrease with decreasing frequency. For objects that are small compared to the wavelength λ of the incident field, Lord Rayleigh's law states that the reflected power from the object is proportional to λ^{-4}. Thus, if a foam panel has a fixed number of small conducting objects in it that are not contacting, the amount of shielding provided by the panel decreases rapidly with decreasing frequency according to Lord Rayleigh's law. This conclusion is consistent with Chen's calculations discussed above.

The preceding analysis has shown that noncontacting fibers that are electrically small (i.e., are much smaller than a wavelength in their major dimension) do not provide effective RF shielding. This conclusion is true even when the number of fibers is large. The wire grid model discussed above reveals that long conductive paths in the direction of the incident electric field are required for effective shielding. Thus, a large number of contacting fibers is required in the foam material to provide effective shielding. Conductive paths must be present in at least two orthogonal directions normal to the incident field to provide shielding for an arbitrarily polarized incident field. Unfortunately, the wire grid model cannot be used to analyze finite length conductors that are not periodic. Hence it is not a general purpose analysis tool for structural foam that is internally loaded with conducting material.

D. Meteorological Model

A great deal of theoretical and experimental work has been performed in the field of meteorological radar. The fundamental calculation of the scattering and absorption of electromagnetic waves by a dielectric sphere is due to Mie and is given in Stratton [8]. Extensive calculations of attenuation, based on Mie's results, have been carried out for rain, hail, fogs and clouds and this data is reported in Kerr [9]. These and other calculations are based on either noncontacting, noninteracting particles or on noncontacting and interacting particles. As was shown in Section IIC, a substantial number of contacts is required between particles to achieve effective shielding from the loaded structural foam. Such a geometry does not appear to be treated in the meteorological radar literature. Hence, meteorological models were abandoned for this study.

E. Predicting Electrical Properties of Panels

The electrical characterization of composite materials is receiving increased attention due to recent use of such materials in aircraft and missiles. Use of these materials is also being contemplated in antennas in order to achieve high dimensional stability as is required for high performance antennas. For the purposes of RF shielding, the effective conductivity (or inversely, the resistivity) of the composite must be known. The higher the effective conductivity the more the composite behaves electrically like a conductor and hence the more shielding that it can provide. The use of carbon fibers in structural foam represents a difficult electromagnetic analysis problem. First of all, the fibers are to some degree wet by the matrix material (which is usually an insulator) and so have an insulating shell around them. Secondly, there is a contact resistance between fibers when they come in physical contact due to their surface properties. Finally the orientation and density of the fibers in the structure is a complicated function of the manufacturing process.

The carbon fibers to be used in RF enclosures made from structural foam are normally received embedded in a matrix material and cut in the form of pellets. The matrix material adheres to the fibers to provide good structural properties. Since the matrix material is usually an insulator, each fiber appears roughly like a wire with an insulating sheath around it. This sheath inhibits electrical conduction between fibers. In addition to this inhibiting factor, surface properties of the fibers and low pressure between fibers tend to retard inter-fiber conduction. The carbon fibers will typically have water, oil and some atmospheric gases absorbed into their surfaces. These surface impurities along with the matrix material constitute an insulating film around the fiber.

Electrical conduction between fibers through the insulating layer can occur in several ways [10, 11]. Because of the wave nature of electrons and because of the distribution of their energies, a certain portion of the electrons can pass through (designated the tunneling effect) a thin film of insulating material, or rather, through a potential barrier which, in the classical sense, would be impenetrable. If the film is less than 20 Angstroms thick, conduction through the film can occur by this tunneling effect. The film acts as an ohmic resistance as long as the voltage across the film does not exceed about 0.5 volts. Films that are 100 Angstroms or more in average thickness are called thick films. Conduction by the tunneling effect can be neglected at these thicknesses. Aside from mechanical fracturing of the film to allow intimate fiber-to-fiber contact, the only other way that current can flow efficiently is to electrically puncture the thick film. Such electrical puncture is called fritting. When the voltage level across a thick insulating film reaches about 10^5 to 10^6 volts/cm, electrons start to flow in selected areas of the film. The areas of current flow are those where the film is thinnest or where its composition makes it more conductive than elsewhere.

This complicated process of forming conduction paths through the network of fibers in a panel makes an exact analysis impossible. Several approaches to obtain an approximate analysis have been attempted. The most promising approach thus far utilizes concepts from the kinetic theory of gases. Work is still being performed in this area. One relationship that has come out of this analysis is that long, thin fibers are better than short, fat ones in regard to improving shielding effectiveness. The reason for this can be explained as follows. Consider a volume of foam with fibers in it. Consider the situation of either long, thin fibers or short, fat ones with the volume of each fiber being fixed. For a fixed number of fibers in the foam, the concentration by weight will be the same for the long and for the short fibers. However, since the fibers are randomly oriented, there is a much greater probability of fiber contact for the long fibers since they can rotate through a much larger volume. In addition, long fibers scatter energy better than short ones as was seen in Section IIC. Thus the conductivity of a panel made from long, thin fibers should be higher than one made from short, fat fibers for the same concentration of fibers by weight.

Several concepts can be obtained from the analysis of Section IIC as to the general nature of the electrical properties of conductively loaded panels. When the conducting particles (be they grains or fibers) are widely separated, there is no contact between particles and hence no significant shielding. Appreciable conductivity starts when the number of particles per unit volume becomes large enough so that there is a significant probability of contact between particles. For 100% concentration, the conductivity of the panel will be that of the particles. Thus, the conductivity of the panel versus particle concentration curve will start at essentially zero for zero concentration, stay at zero until the concentration is high enough to cause significant physical contact between particles, and then rise and finally approach the conductivity of the particles for 100% concentration. The concentration at which the conductivity begins to increase from zero depends on the particle characteristics. As will be seen in Section IIIB, a 30% concentration of aluminum coated glass fibers has a much lower conductivity than a 10% concentration of carbon/graphite fibers. This difference is probably due to an oxide layer on the aluminum which inhibits interfiber contacts and low fiber conductivity due to the thinness of the coating.

Carbon and graphite fibers can be made from precursors of rayon, polyacrylonitrile (PAN), or pitch. The principal application of rayon was, until recently, in the manufacture of cord for automobile tires. However, rayon is no longer used in tires and the sources of rayon fiber have almost completely ceased production. Fibers made from pitch are typically more highly graphitized and have a higher modulus than PAN fibers. Pitch fibers also show longer ordering of crystals in the fiber than do PAN fibers. Since there is a direct relationship between the fiber's modulus and its basal plane conductivity, the higher the modulus the higher will be the conductivity of the fiber. This appears to be caused by a stronger alignment of the crystal basal planes with the fiber axis as the modulus increases.

The above considerations suggest the use of pitch based fibers with as high a modulus as possible to achieve the highest electrical conductivity possible and hence the best shielding. It appears that the present panels made by AMMRC use PAN-based Hercules AS fibers. The fiber conductivity could be increased by about a factor of 10 by using a high modulus pitch fiber such as Union Carbide VM0034, TP4104B, or TP4101. An alternate material that should be considered if the preceding ones cannot be obtained is the PAN-based fiber GY-70 made by Celanese. Its conductivity is about 3 times better than Hercules AS and so should produce a factor of 3 increase in conductivity instead of the factor of 10 that is required for 50 dB of shielding effectiveness (see Section IIA). The fibers just recommended have good surface contact properties in addition to having high bulk conductivity and are recommended for use in Phase II of the program.

F. Alternate Materials

Materials other than carbon/graphite fibers were considered for internally loading the structural foam. Metalized glass fibers, metal powders and magnetic (high permeability) powders were considered. Metalized glass fibers are often used as chaff material and so are readily available. The conductivity of metal coated fibers can be much higher than that of carbon/graphite fibers depending on the thickness of the metal and so have the potential of providing better shielding. The conductivity will be low, however, if a thin, discontinuous metal coating is used. Aluminum is the metal typically used to coat the glass fibers. Aluminum suffers from an oxide layer that quickly builds up on its surface and which inhibits conduction between fibers (a property of little concern in chaff work). Section IIIB presents measured conductivity data showing substantially worse performance from metalized glass fibers than from carbon/graphite fibers. Gold coated fibers would not build up an oxide surface layer like aluminum and would have a much higher conductivity than the carbon/graphite fibers. However, it does not appear that gold fibers would be economical. Thus metalized glass fibers do not offer a practical method for improving shielding effectiveness.

Metallic powder, in particular silver powder, is used commercially in conducting pastes and calking materials for RFI shielding applications. Conversations with one of the manufacturers of such material, namely Emerson &

Cuming, revealed that the concentration of silver powder had to be about 80% (the exact value is company proprietary) in order to achieve satisfactory shielding. Such a concentration would not be economical and would not produce the desired mechanical properties from the foam panels. Lower concentrations will produce less shielding as is the case with the use of fibers in the foam. The amount of shielding achievable from lower concentrations such as 30% is not known. A review of measured data [12] taken at Georgia Tech on higher concentrations suggests that large particles provide better shielding than do fine ones. This is expected to be the case for lower concentrations also. This same report also indicates that high permeability powders such as carbonyl iron or ferrite powders such as General Ceramics, Inc. T-1,O-3 or H provide higher absorption loss than do metal powders. The metal powders on the other hand provide higher reflection loss but little absorption loss. Thus a combination of metallic and magnetic powders in one panel is recommended in an attempt to achieve both high reflection and high absorption loss. Alternate materials which might be less expensive but have the same electrical properties are made by the Metals Division of the Glidden Company. Glidden material number D-290 is similar to carbonyl iron and M-180 to General Ceramics H type ferrite powder. The ferrite powders are recommended [12] over carbonyl iron since they have higher loss at low frequencies than does carbonyl iron. Silver is recommended for the metal powder.

III. MEASUREMENTS

A. Preliminary Measurements

Preliminary shielding effectiveness measurements were performed on prototype panels supplied to Georgia Tech by AMMRC. These measurements were reported in [13] and provided a test of the measurement configuration. These measurements indicated that certain improvements had to be made to the equipment during the second phase of the contract. Greater care would have to be exercised in making the measurement enclosure in order to measure larger values of shielding effectiveness (i.e., the dynamic range of the measurement system would have to be increased). Basically this involved using better RF seals where cables enter the box. In addition, a better box had to be designed and different antennas selected in order to extend the measurements down to 10 MHz.

Measurements of the bulk conductivity of the panels showed that greater shielding was obtained from panels with higher conductivity. These measurements confirmed the trends predicted by Figure 2, and they provide a quick means of assessing the relative shielding effectiveness of a material. Recommendations were also made for panels to be built for the Phase II testing and measured data taken on these panels are presented in the next section of this report.

B. Shielding Effectiveness Measurements

The shielding effectiveness of nineteen test samples was measured and recorded over the frequency range of 10 to 1000 MHz. Fiberfil in Evansville, Indiana compounded the materials in the panels for these measurements. The shielding effectiveness of a test sample was determined as the difference between the fields coupled through an aperture with and without the sample present. The measurement configuration utilized during these evaluations is illustrated in Figure 8. The aperture is located in one wall of a 2-foot cube aluminum test chamber. Selected views of this test chamber are presented in Figure 9. The purpose of the test chamber is to isolate the transmitting and receiving antennas such that the only coupling between them is through the aperture. To minimize unwanted coupling (i.e., leakage), all permanent seams of the chamber were welded and finger stock was installed to seal the panel test port

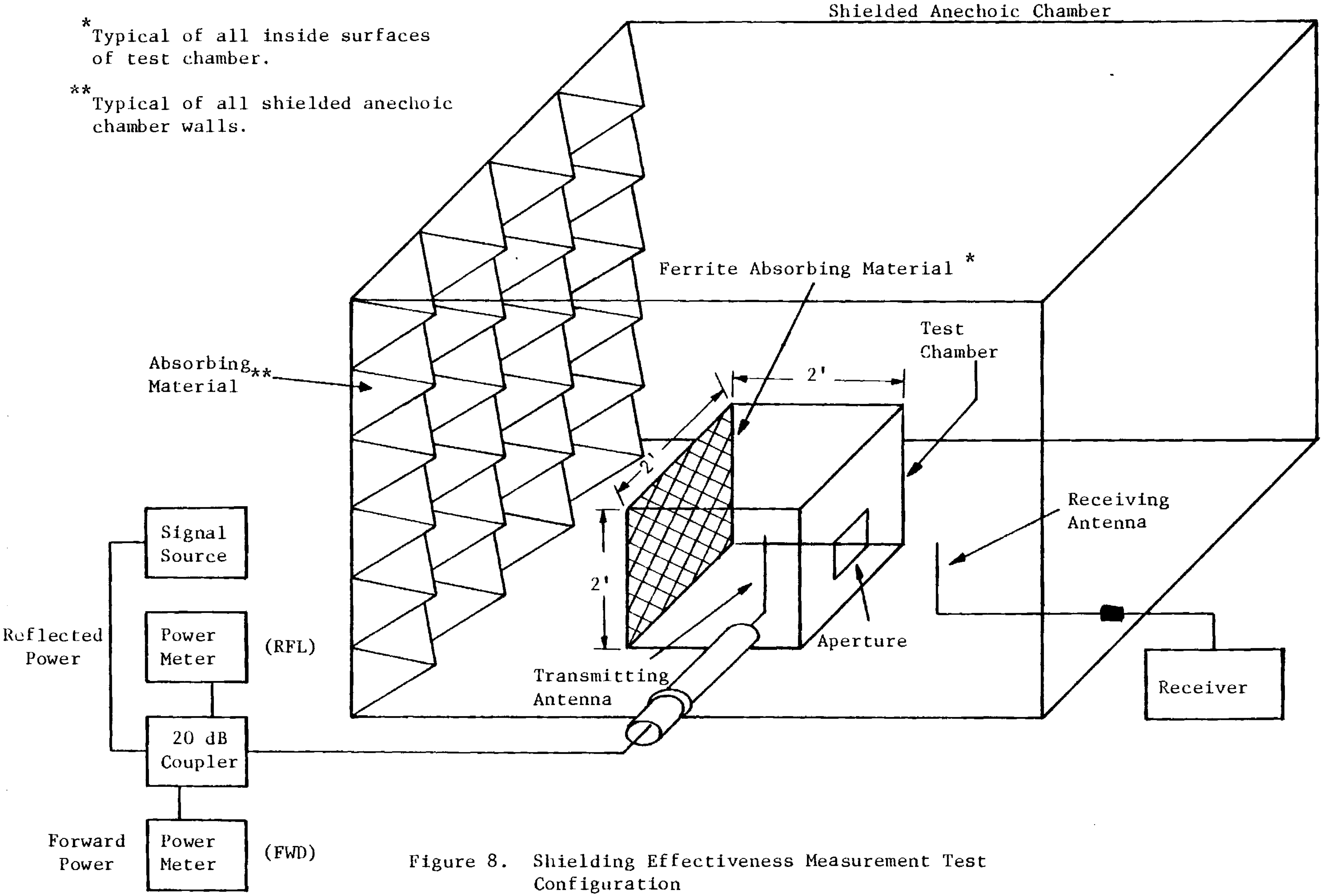
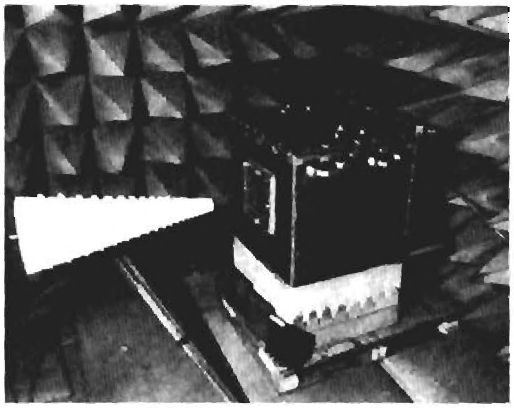
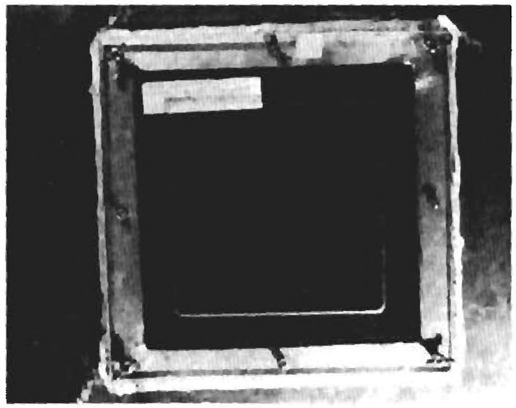


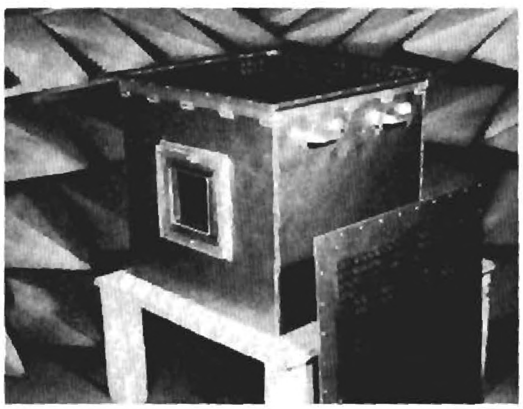
Figure 8. Shielding Effectiveness Measurement Test Configuration



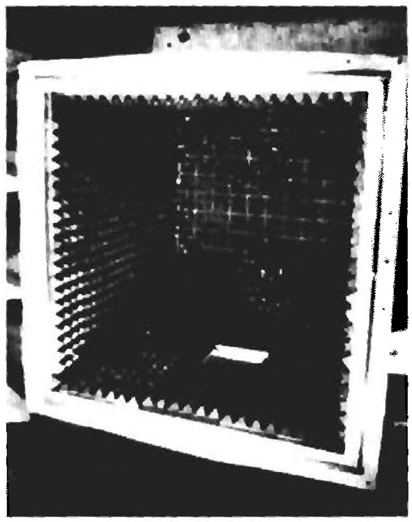
a) Test chamber



b) Test port



c) Test chamber with top removed



d) Interior of test chamber

Figure 9. Selected Views of Shielding Effectiveness Test Chamber.

(aperture) and the lid of the chamber. The inside of the test chamber was lined with Emerson and Cuming, Inc. NZ-1® ferrite absorbing material to reduce the coupling between the transmitting antenna and the metallic walls, and thus permit generation of the necessary low frequency fields with less required power from the source.

To isolate the test setup from the external EM environment, the test chamber and receiving antenna were located in a shielded anechoic room. The isolation characteristics of this room are 100 dB or greater over the frequency range of interest for this program. The chamber was connected to the outside of the room via a length of 1/2 inch copper pipe. One end of the pipe was soldered to the rear part of the chamber and the other end was soldered to an access hole in one wall of the shielded room. A coaxial cable through the copper pipe connects the transmitting antenna in the test chamber to its signal generator system located outside the shielded room. This cable routing configuration was used to minimize RF leakage from the coaxial cable and thus increase the dynamic measurement range of the test setup.

The dynamic range of the test setup was determined by comparing the field coupled through the open aperture with that field coupled through a 3/16 inch thick aluminum plate positioned over the aperture. The measured dynamic range is presented as a function of frequency in Figure 10.

The antennas utilized during the tests are listed in Table I. As seen from this table, the tests were performed using two types of transmitting antennas: a commercially available magnetic loop and a set of electric dipole probes developed at Georgia Tech. The dipoles utilize a combination of dielectric loading and capacitive end-loading to increase their effective electrical length. During the tests, the transmitting antenna was positioned in the test chamber such that its geometric center coincided with that of the chamber. The receiving antenna was located external to the chamber and approximately two feet from the geometric midpoint of the test sample. Limited tests were conducted to ensure that the results were not dependent upon which antenna was used for transmitting and receiving. The functions of the two antennas were reversed, i.e., the antenna in the test chamber was used for receiving and the outside antenna was used for transmitting. The resulting shielding effectiveness data showed no significant dependence (less than 1 dB variation) on which antenna was used for which function.

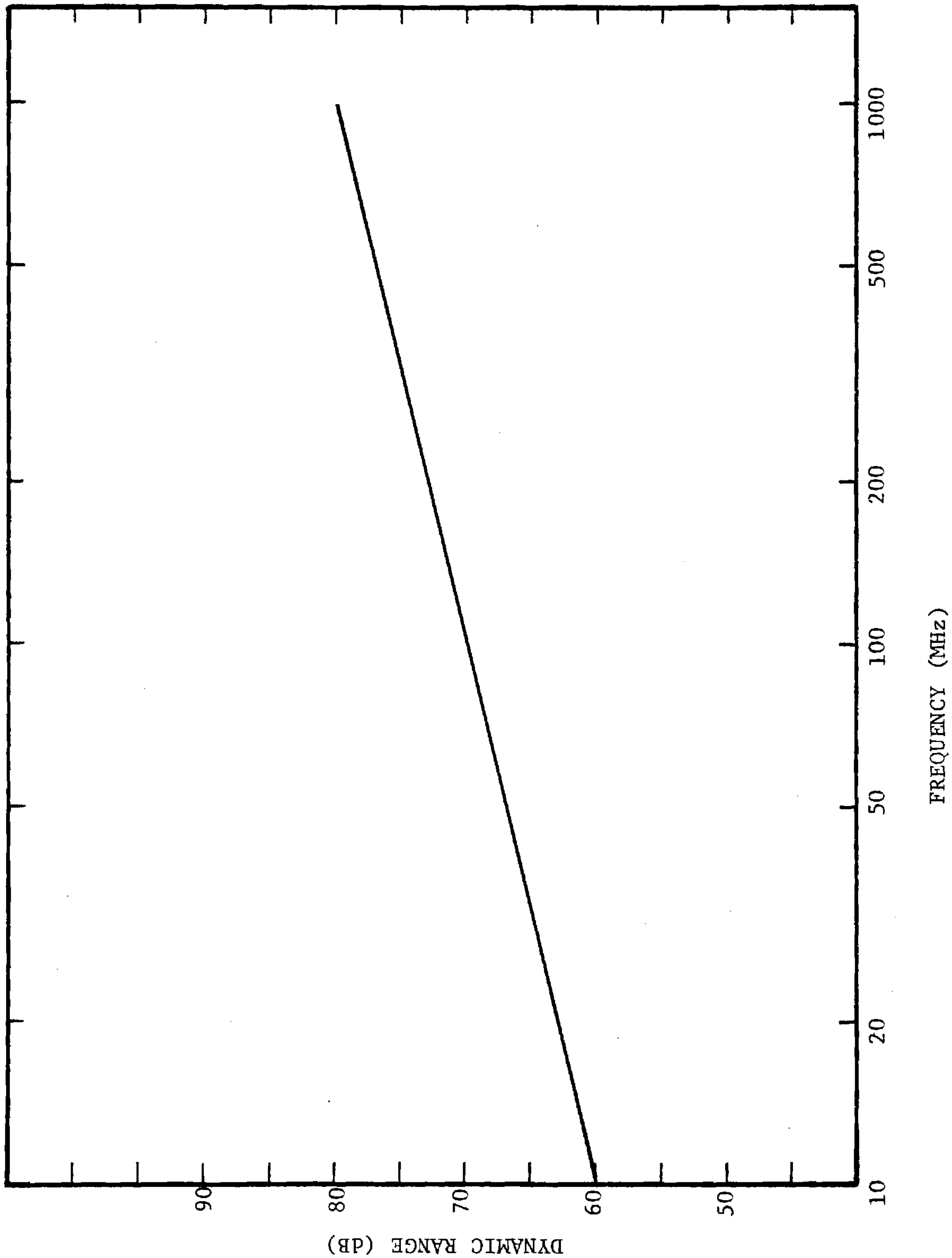


Figure 10. Measured Dynamic Range of Shielding Effectiveness Measurement Setup

TABLE I

SUMMARY OF ANTENNAS USED IN THE MEASUREMENT
OF SHIELDING EFFECTIVENESS

Frequency Range (MHz)	Transmitting Antenna	Receiving Antenna
10 to 30	Magnetic loop	Magnetic loop
	Electric dipole	Biconical
30 to 200	Magnetic loop	Biconical
	Electric dipole	Biconical
200 to 1000	Magnetic loop	Log conical
	Electric dipole	Log conical

The signal generating system consisted of a source, two power meters, and a bi-directional coupler (see Figure 8). The signal is routed through the coupler to the coaxial cable in the copper pipe. For matching purposes, a 6 dB fixed attenuator was placed in the coaxial line near the transmitting antenna. The bi-directional coupler was used to couple the forward and reflected power to the two power meters for monitoring.

Shielding effectiveness was measured by adjusting the signal source to a predetermined level and recording the receiver reading with the aperture open. The test panel was then placed in position, using a bulkhead test fixture over the aperture, and the received signal level again recorded. A comparison of the receiver reading obtained when the panel is installed with the receiver reading obtained with the aperture open yields the shielding effectiveness of the test sample. This procedure was repeated for twenty discrete frequencies between 10 MHz and 1 GHz to ensure comprehensive coverage. The molding conditions and test matrix for these plaques are given in Tables II and III. All polycarbonate plaques shown were fabricated starting with 1/2 inch fibers in pellet form. Each plaque was 0.25 inch thick and foamed to a 20% density reduction. The results of the shielding measurements are presented in Figures 11 through 29.

C. Discussion of Results

The dynamic range of the measurement system determines the maximum value of shielding effectiveness (SE) that can be reliably measured. The measured dynamic range of the measurement set-up varied linearly from a minimum value of 60 dB at 10 MHz to a maximum value of 80 dB at 1,000 MHz (see Figure 10). All measured values of SE were well below these values and so they were not limited by the measurement sensitivity.

The frequency range over which measurements were performed covers several important radio frequency bands. The high frequency (HF) band covers 3-30 MHz, the very high frequency (VHF) band covers 30-300 MHz, while the ultra-high frequency (UHF) band covers 300-3,000 MHz.

Figure 11 demonstrates that no shielding is observed when no filler is added to the plaque. This figure demonstrates that the measurement configuration is performing as expected over the entire frequency range of operation.

Figures 12-14 show the measured SE for Lundy RoMHOglas (aluminum coated) glass fibers of 15, 25, and 40% by weight concentrations, respectively. The

TABLE II

PROCESS CONDITIONS FOR MOLDING POLYCARBONATE
STRUCTURAL FOAM PLAQUES

Machine	13.0 ounce Battenfeld BSKM
Nozzle Type and Opening	Standard 3/16 inch
Cylinder Temperature	Rear - 540°F Middle - 570°F Front - 590°F
Nozzle Temperature, % variance	30%
Mold Temperature	160°F
Screw Speed R.P.M.	75
Plasticizing Back Pressure	150
Inject with Rotating Screws, yes/no	No
Plasticizing Time	20 seconds
Time of Injection Pressure	10 seconds
Total Time for Injection	30 seconds
Injection Pressure	1800 psi
Cooling Time	30 seconds
Open Cycle Time	2 seconds
Total Cycle Time	62 seconds
Type Mold Release	None

TABLE III

TEST MATRIX FOR CONDUCTIVE FIBER REINFORCED POLYCARBONATE STRUCTURAL FOAM[1]

FIBER	TYPE	FIBER LENGTH[2]	CONCENTRATION (%)		
Lundy RoMHOglas	Aluminum/Glass	1/2"	15	25	40
Lundy RoMHOglas	Aluminum/Glass	3/4"	15	25	40
Union Carbide VMD	Pitch	Milled	--	25	40
Union Carbide VSB-32-T	Pitch	1/2"	--	25	40
Hercules AS-4/1805	PAN	1/2"	15	25	40
Cleanese GY-70	PAN	1/4"[3]	--	25	40
Union Carbide VSB-32-T Lundy RoMHOglas	Pitch/Aluminum Glass (3/1)	1/2"	--	--	40
Union Carbide VSB-32-T Lundy RoMHOglas	Pitch/Aluminum Glass (1/1)	1/2"	--	--	40
Union Carbide VSB-32-T Lundy RoMHOglas	Pitch/Aluminum Glass (1/3)	1/2"	--	--	40
UNFILLED	--	-	--	--	--

1. Foamed to a 20% density reduction

2. Fiber length prior to injection molding and after compounding

3. Fiber length prior to compounding

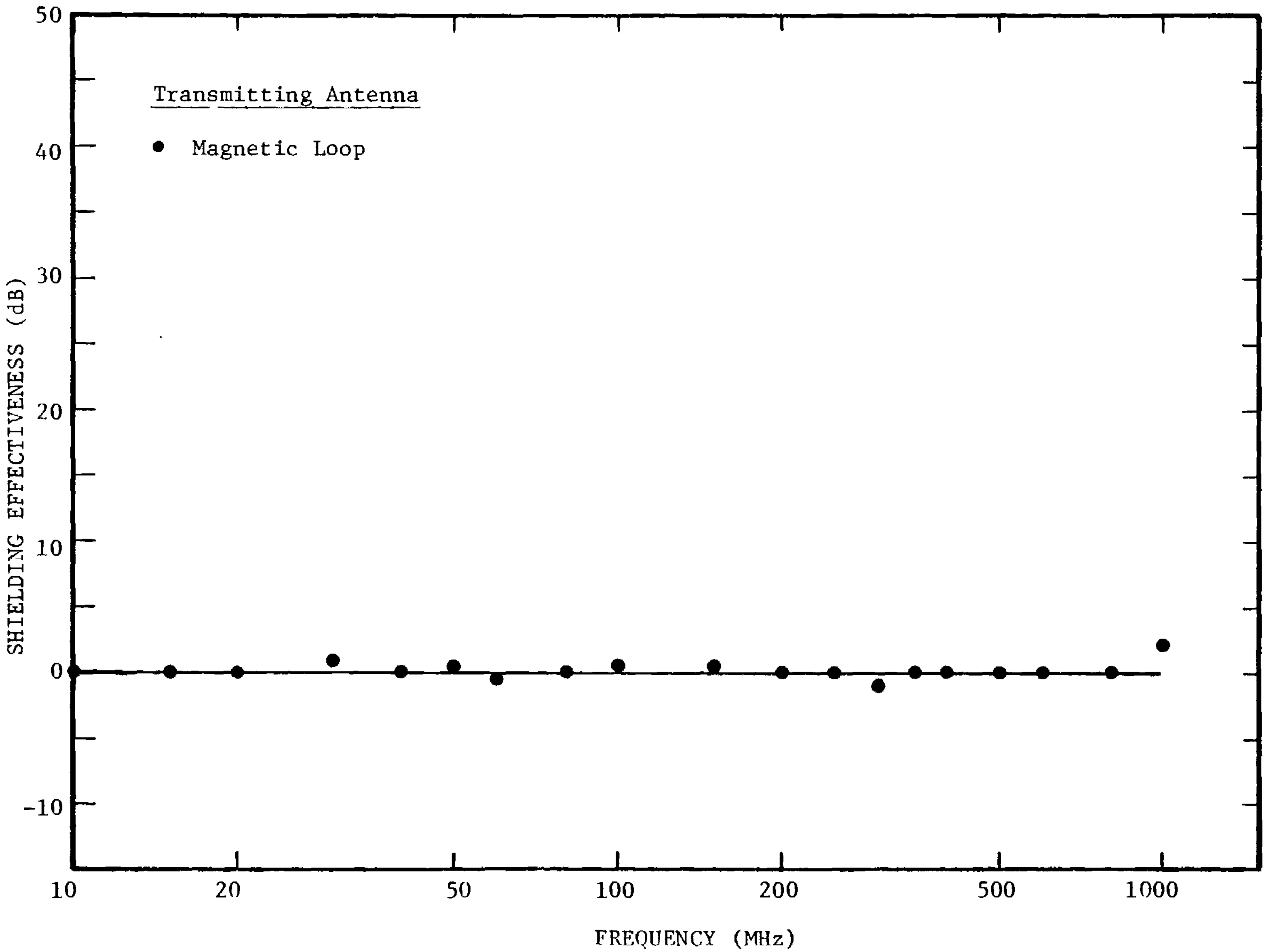


Figure 11. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque with no Filler

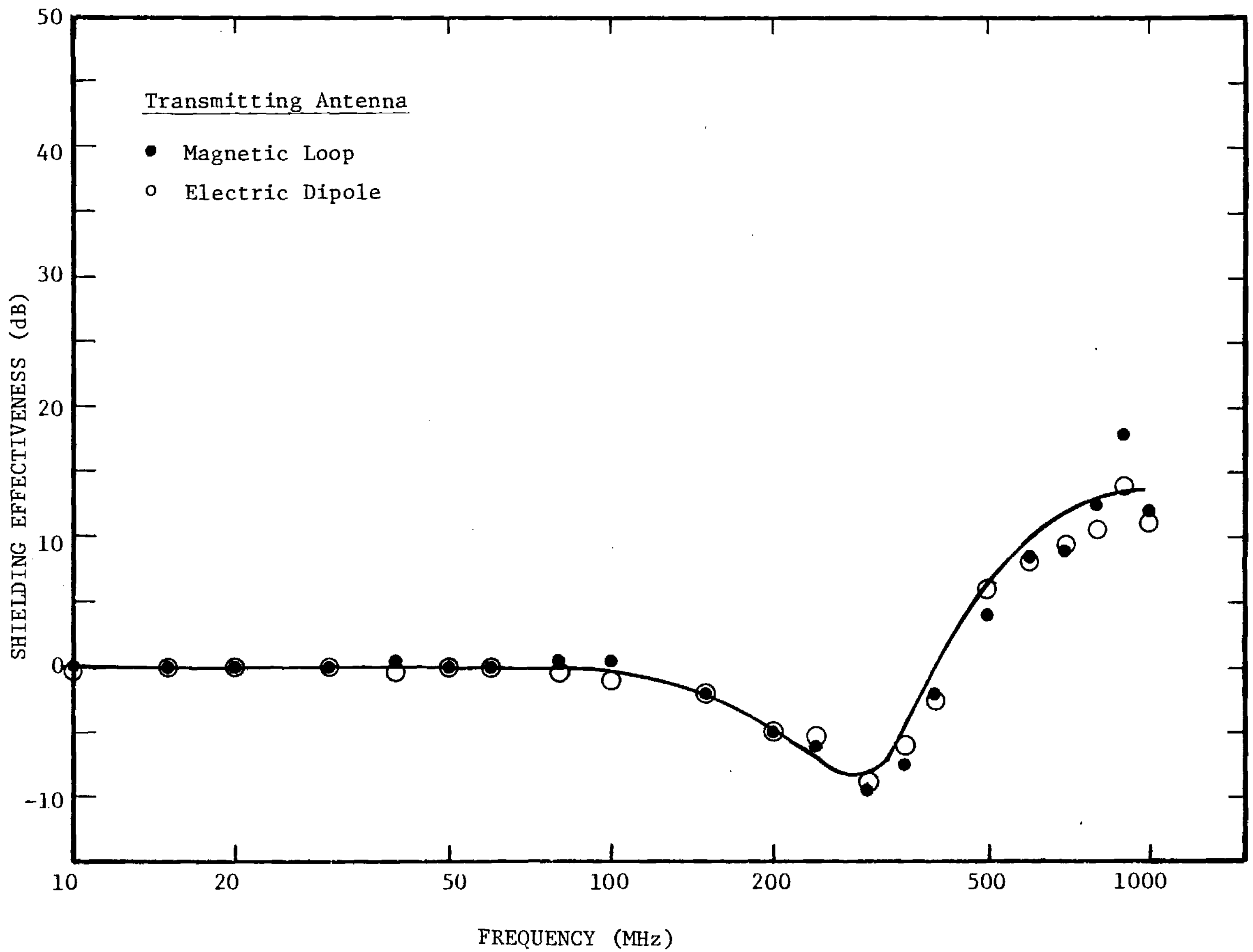


Figure 12. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 15% by Weight of Lundy RoMHOglas and Fibers Initially 0.5 Inch Long

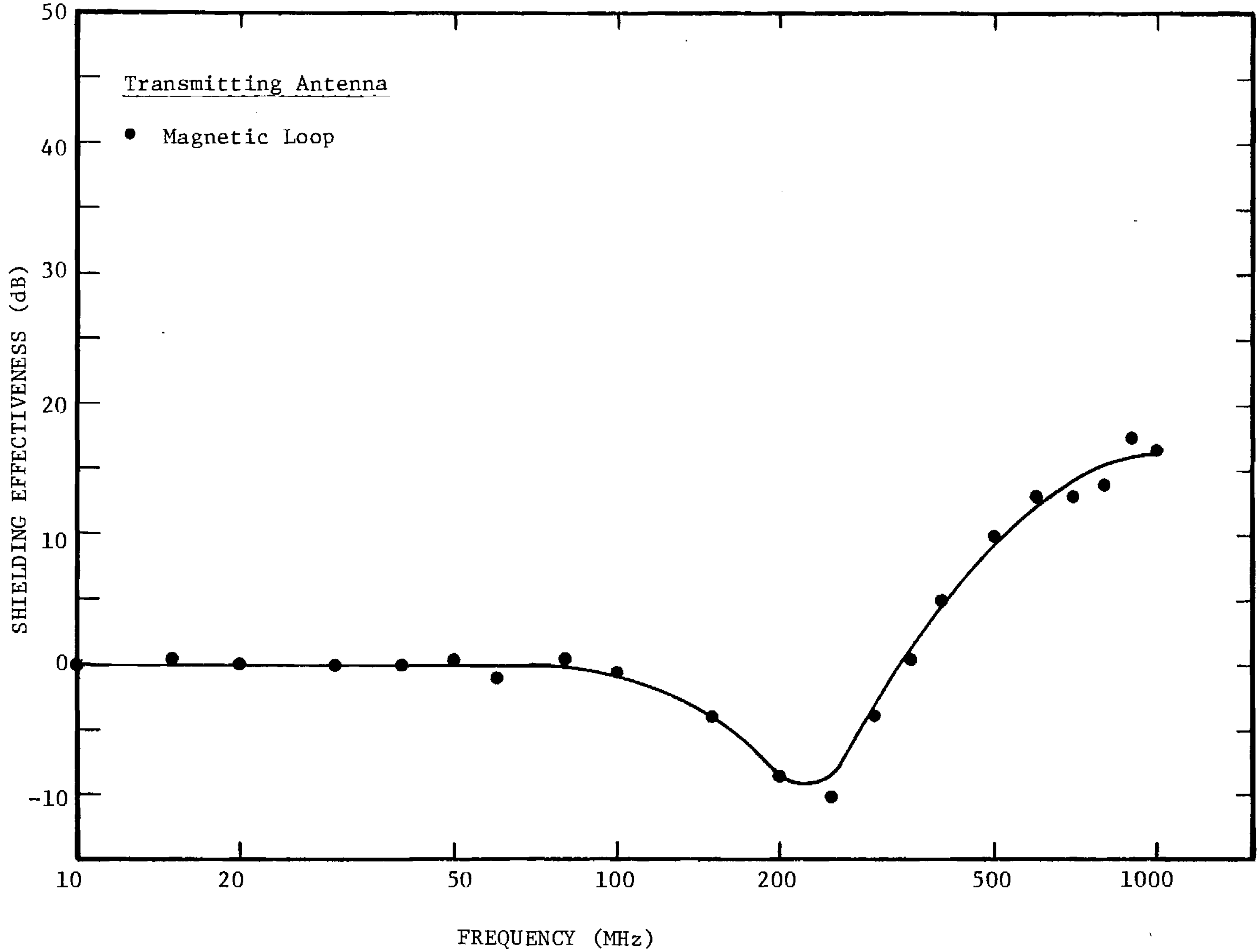


Figure 13. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 25% by Weight of Lundy RoMHOglas and Fibers Initially 0.5 Inch Long

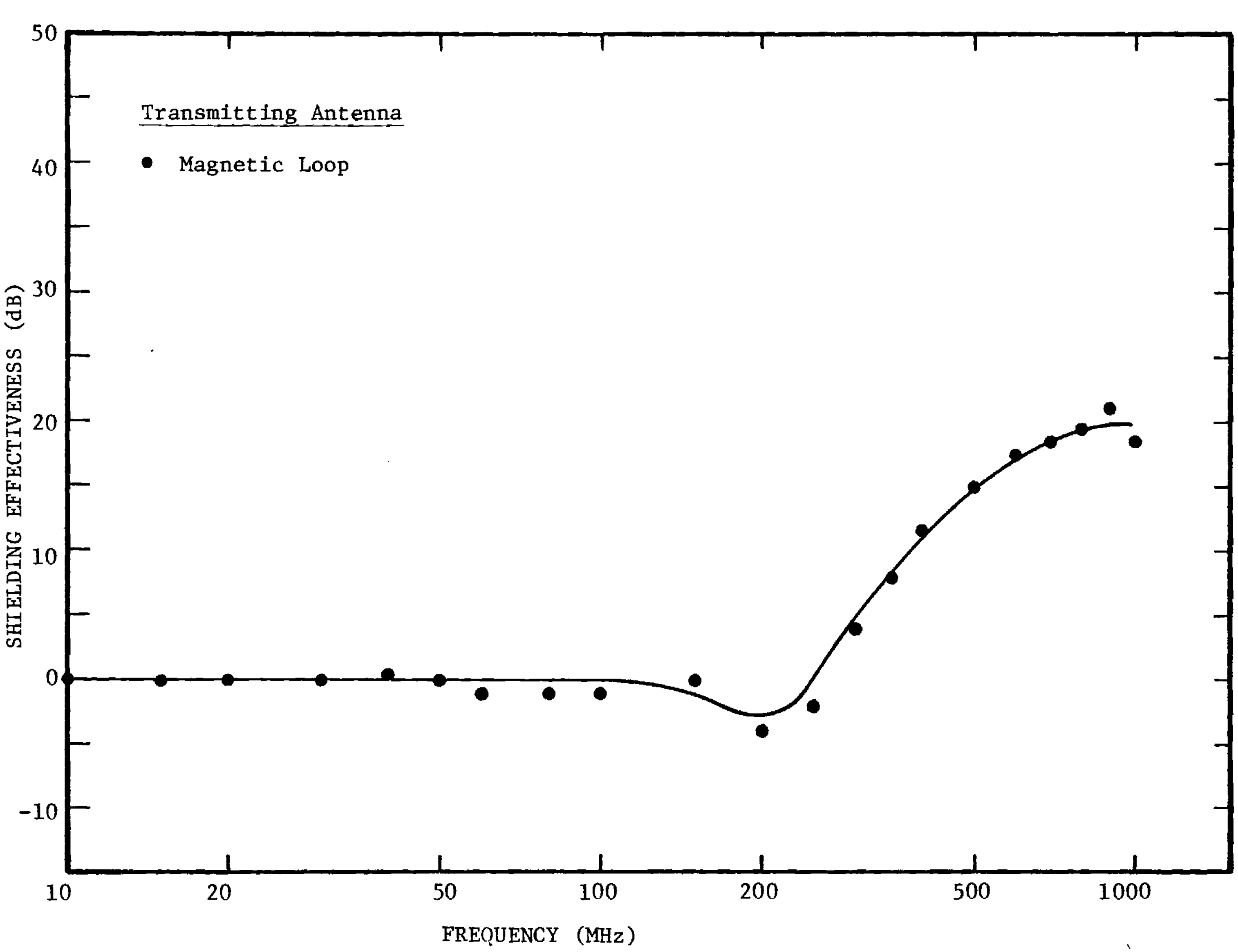


Figure 14. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 40% by Weight of Lundy RoMHOglas and Fibers Initially 0.5 Inch Long

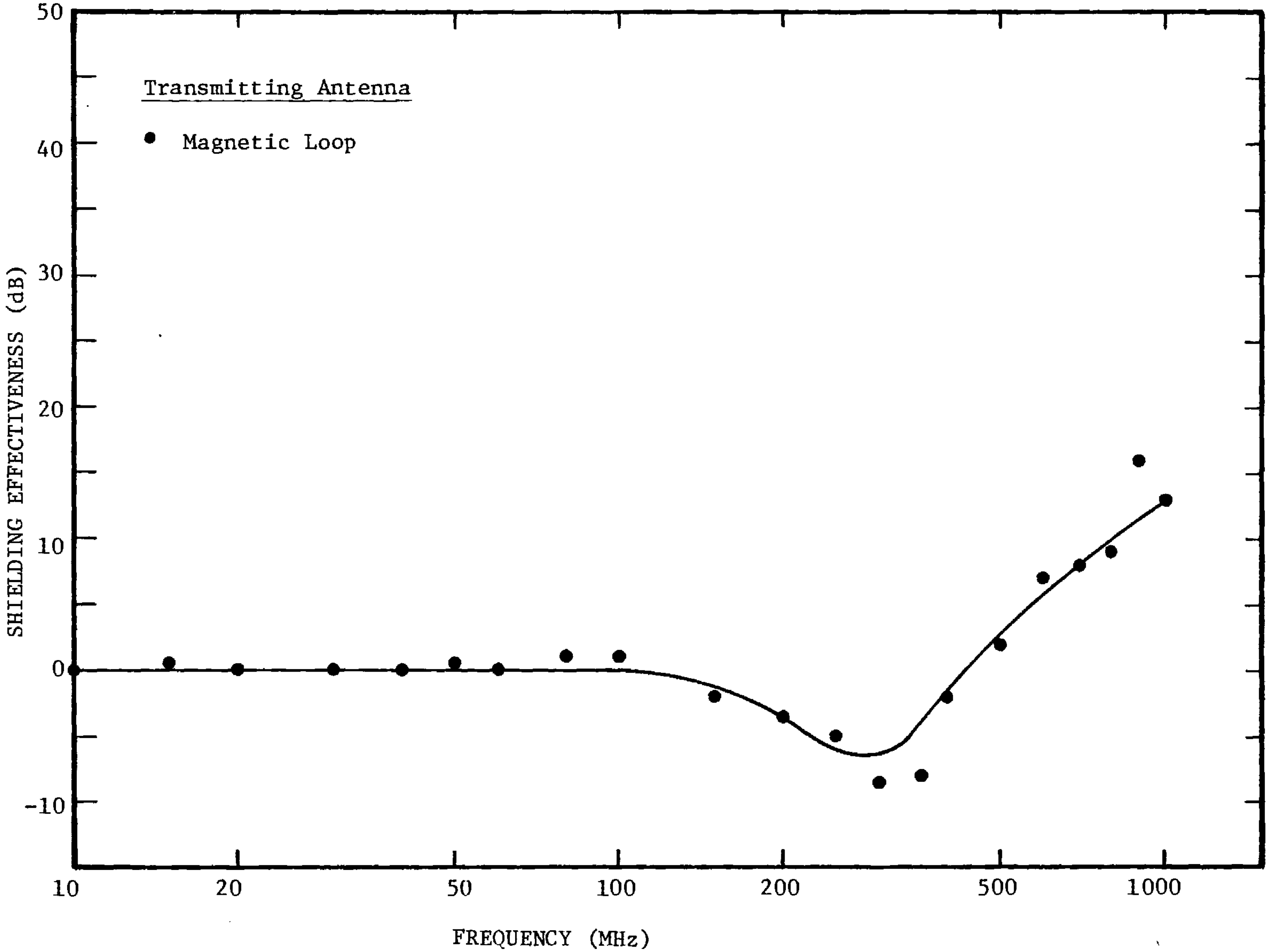


Figure 15. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 15% by Weight of Lundy RoMHOglas and Fibers Initially 0.75 Inch Long

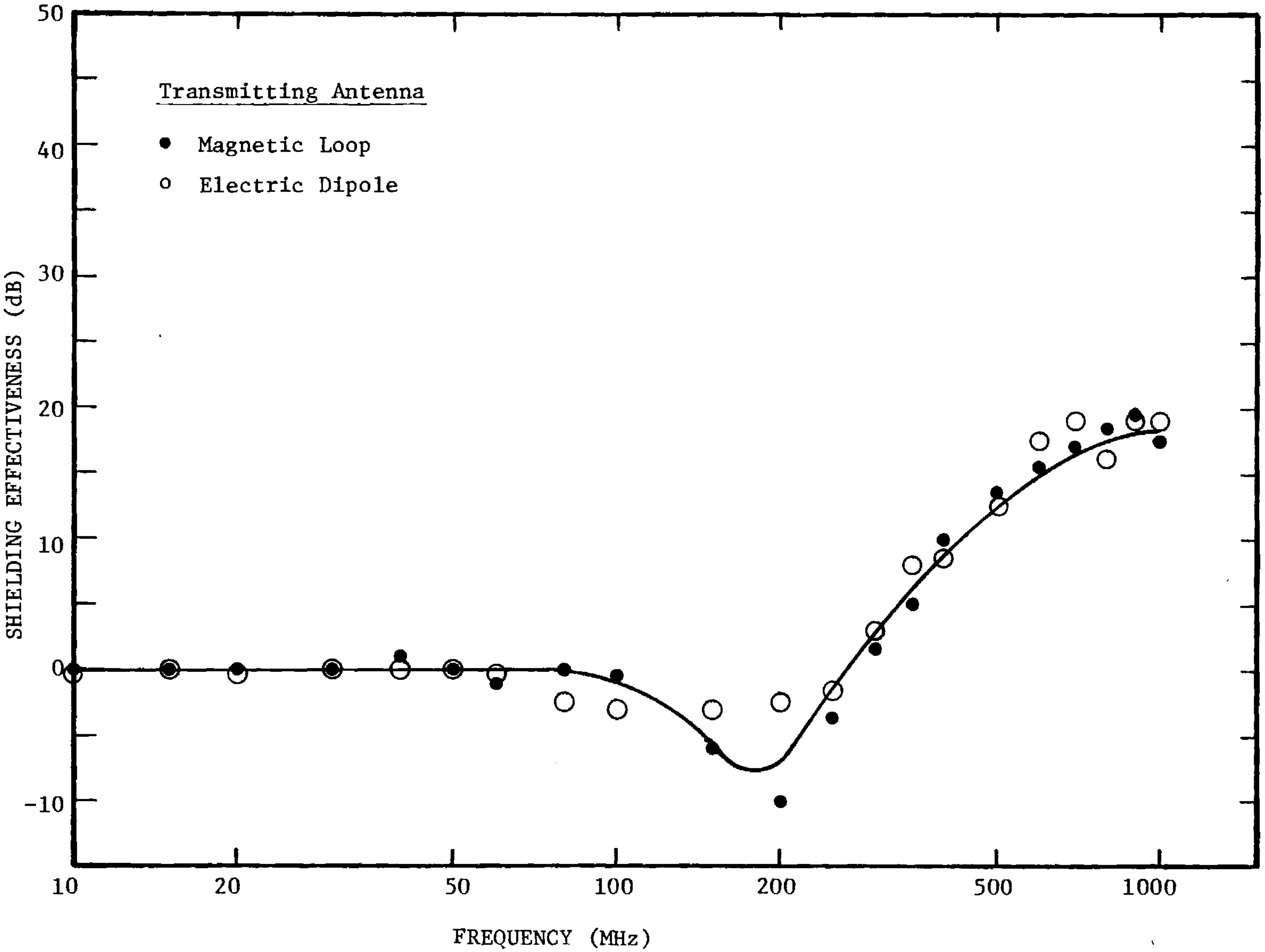


Figure 16. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 25% by Weight of Lundy RoMHOglas and Fibers Initially 0.75 Inch Long

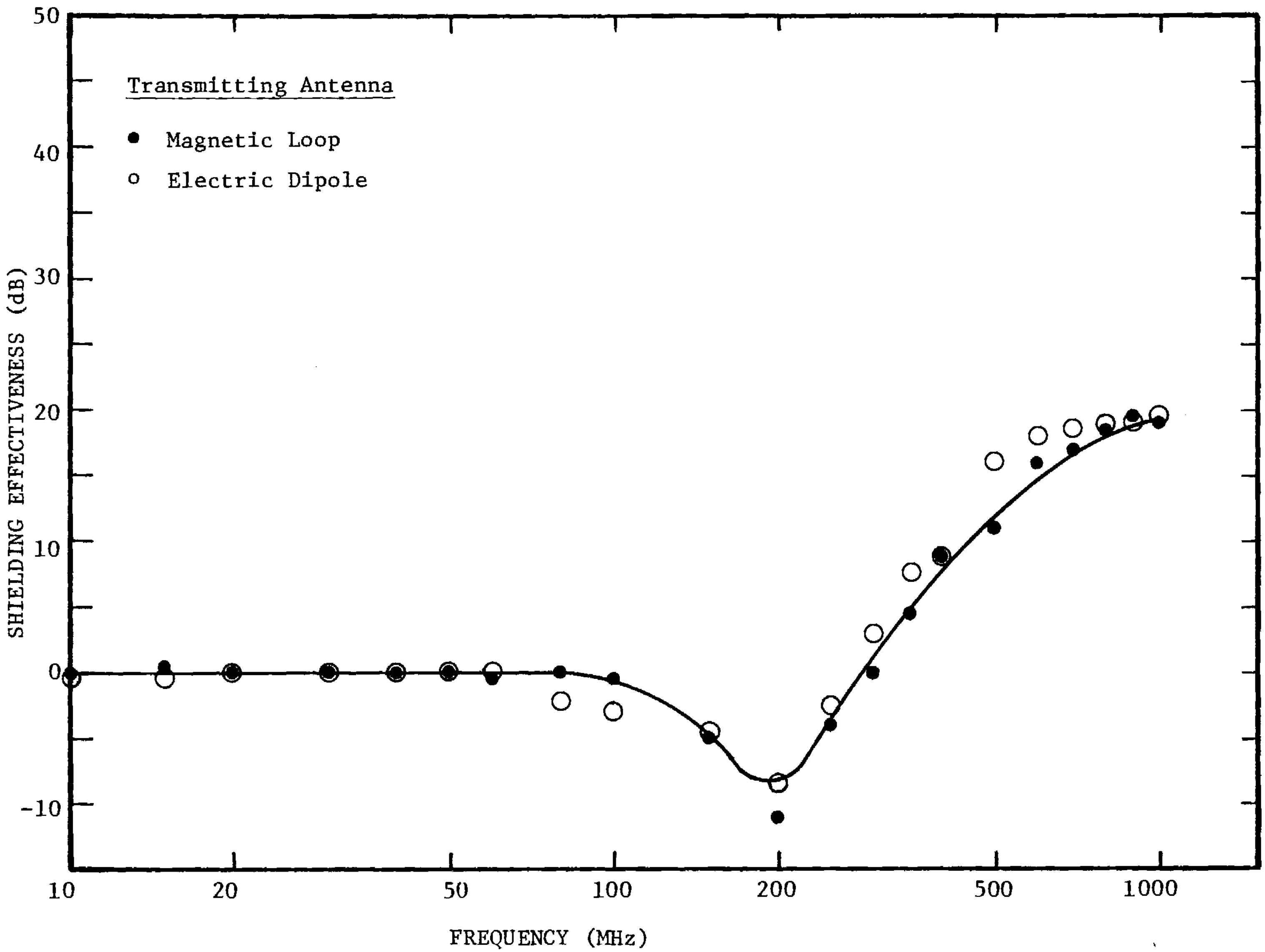


Figure 17. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate, Structural Foam Plaque Filled with 40% by Weight of Lundy RoMHOglas and Fibers Initially 0.75 Inch Long

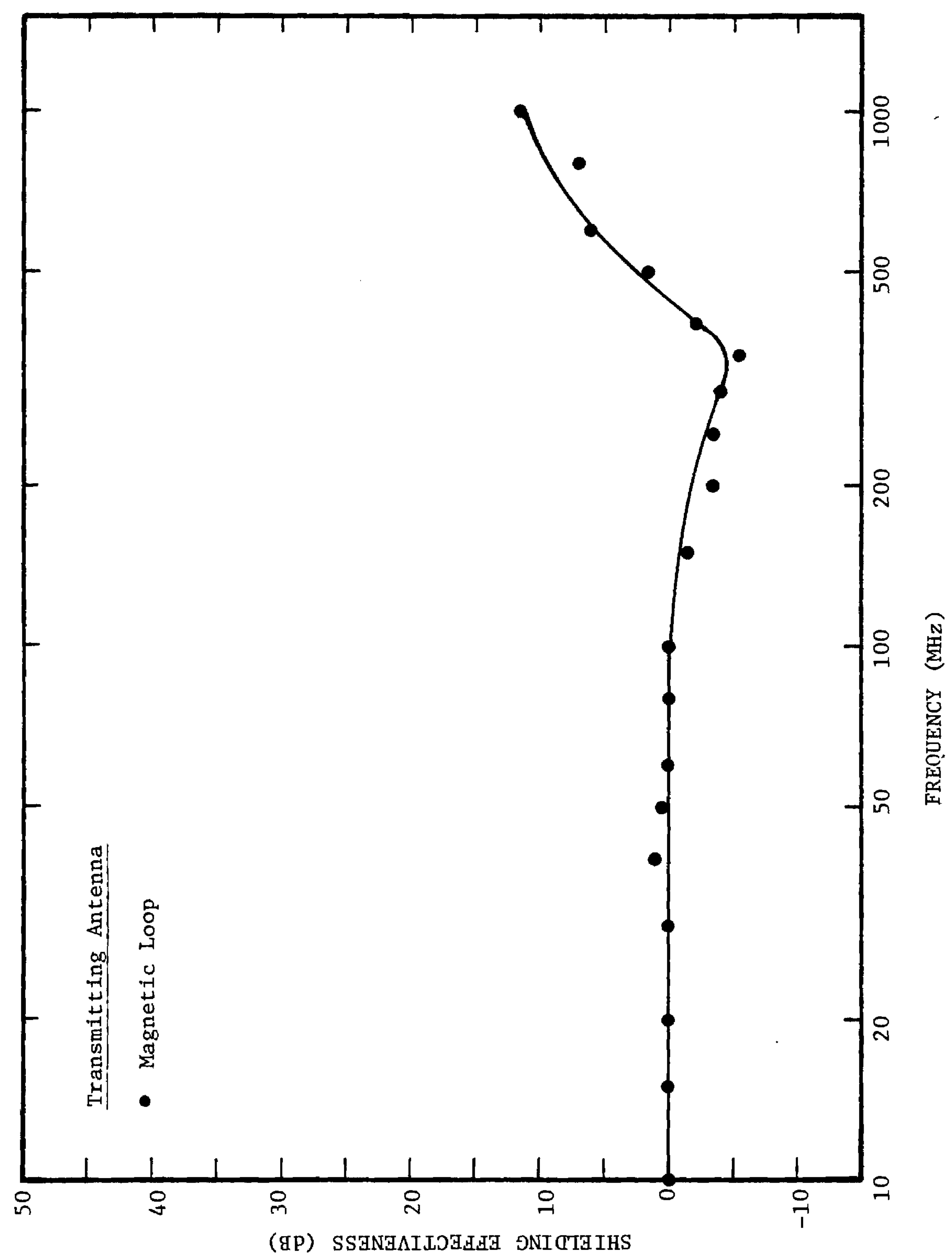


Figure 18. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 25% by Weight of Union Carbide Thornel VMD Fibers

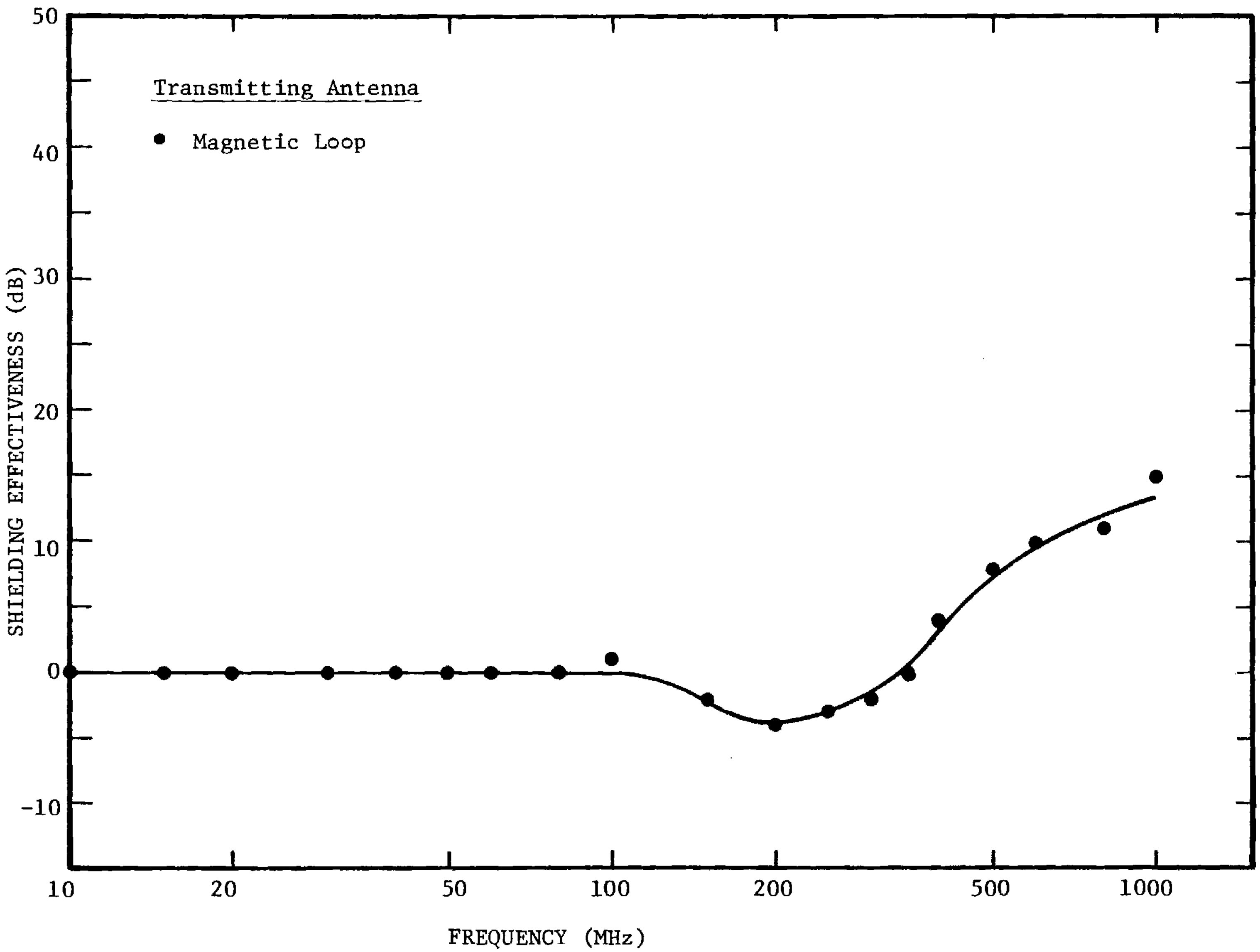


Figure 19. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 40% by Weight of Union Carbide Thornel VMD Fibers

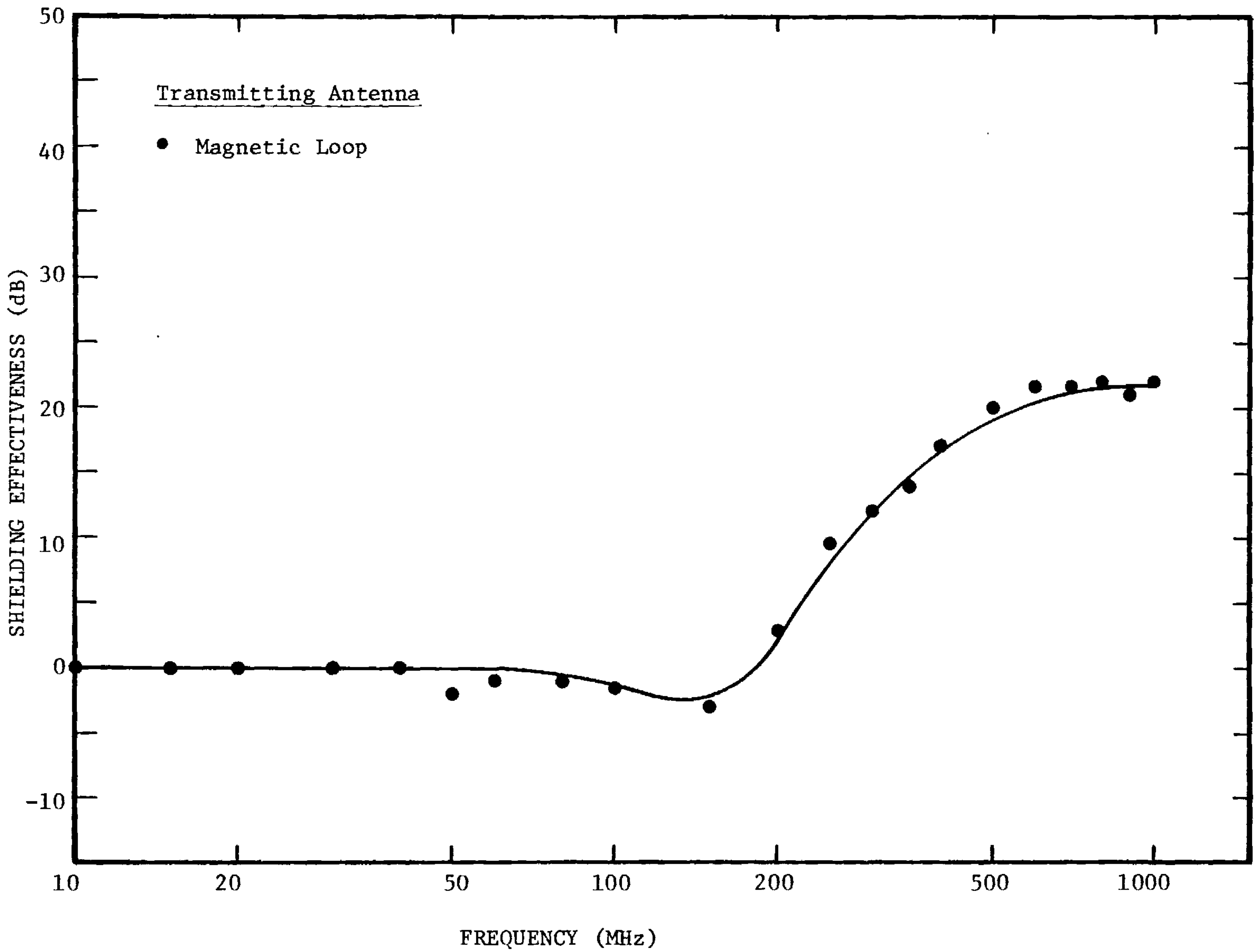


Figure 20. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 15% by Weight of Hercules AS-4/1805 and Fibers Initially 0.5 Inch Long

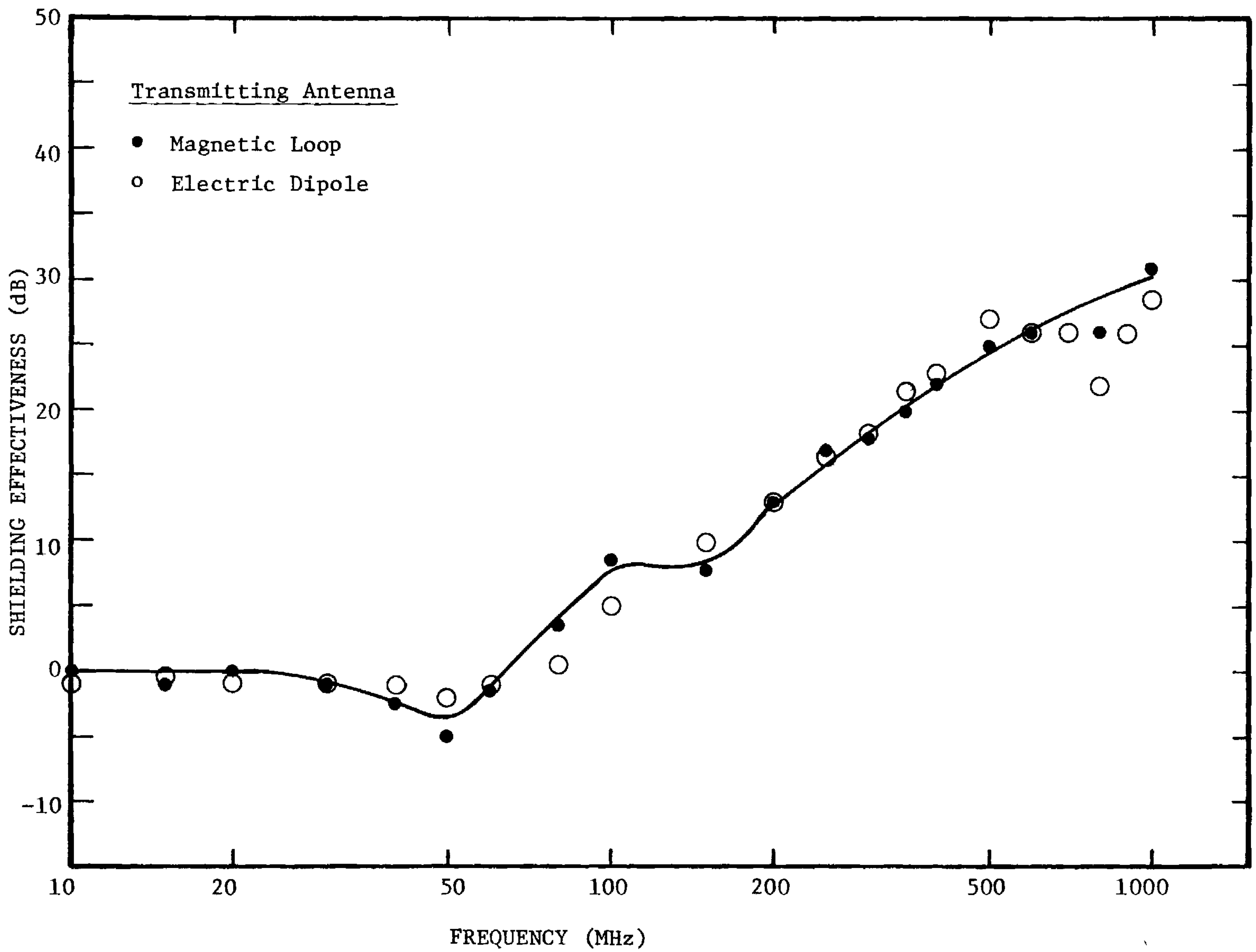


Figure 21. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 25% by Weight of Hercules AS-4/1805 and Fibers Initially 0.5 Inch Long

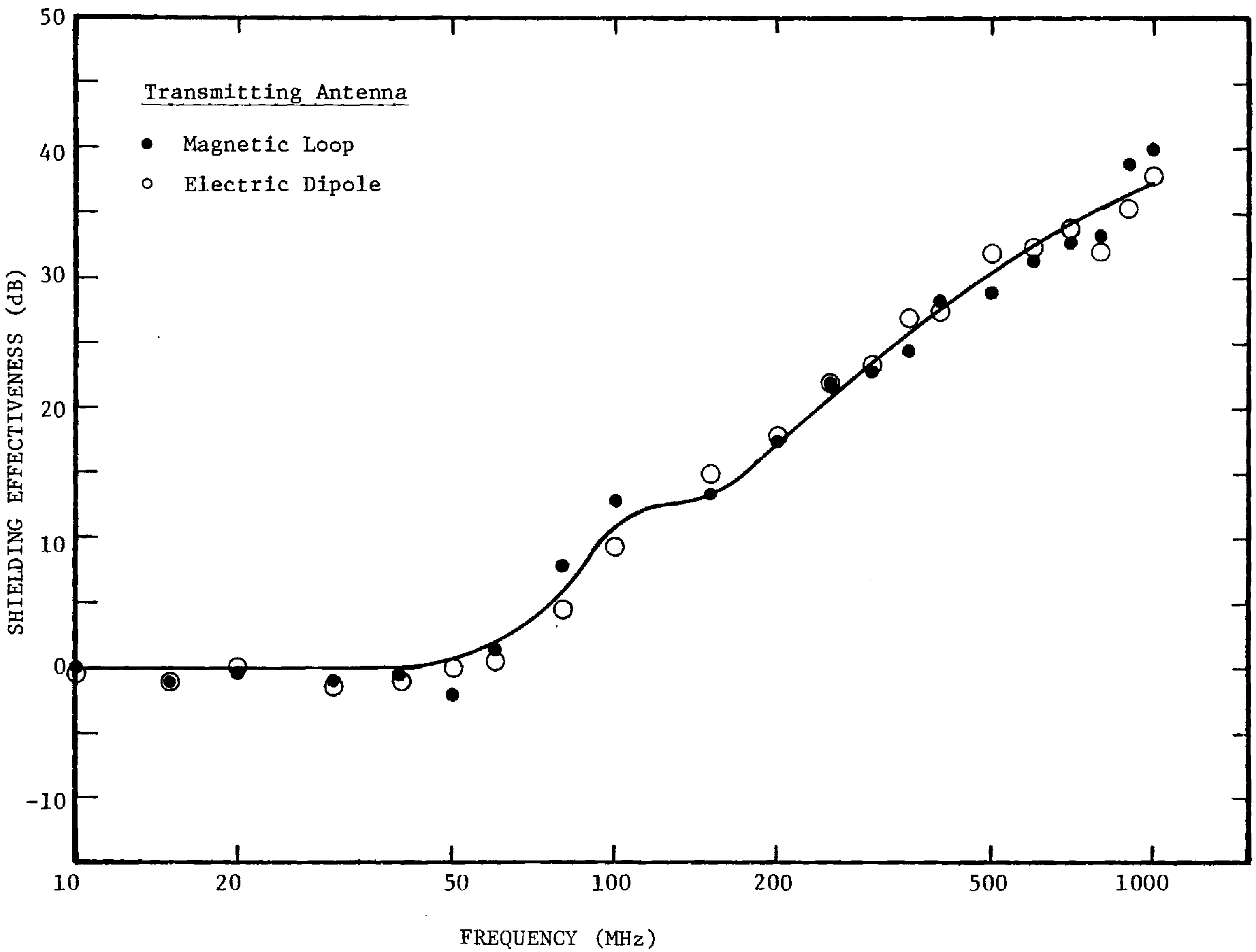


Figure 22. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 40% by Weight of Hercules AS-4/1805 and Fibers Initially 0.5 Inch Long

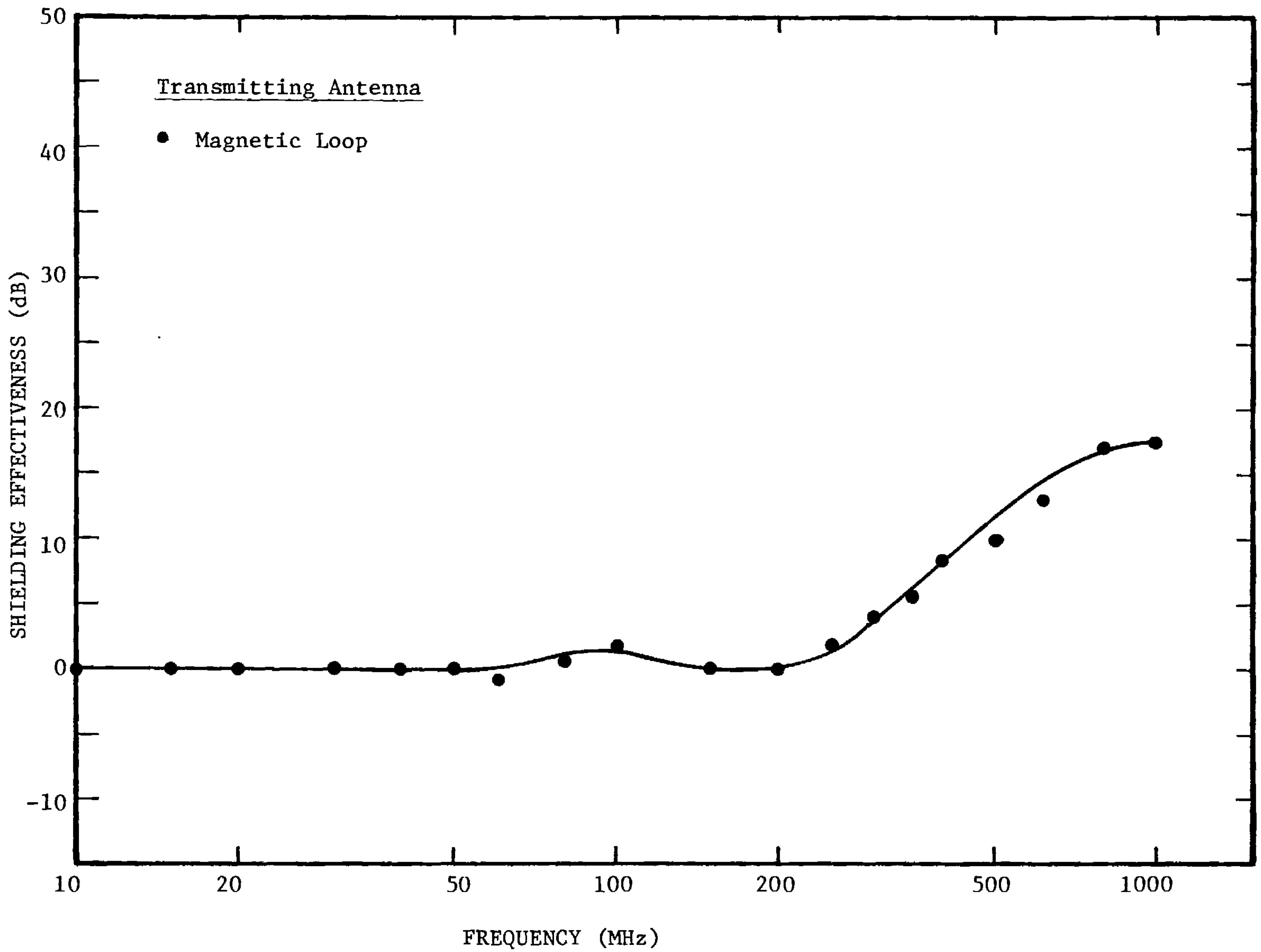


Figure 23. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 25% by Weight of Celanese GY-70 Fiber

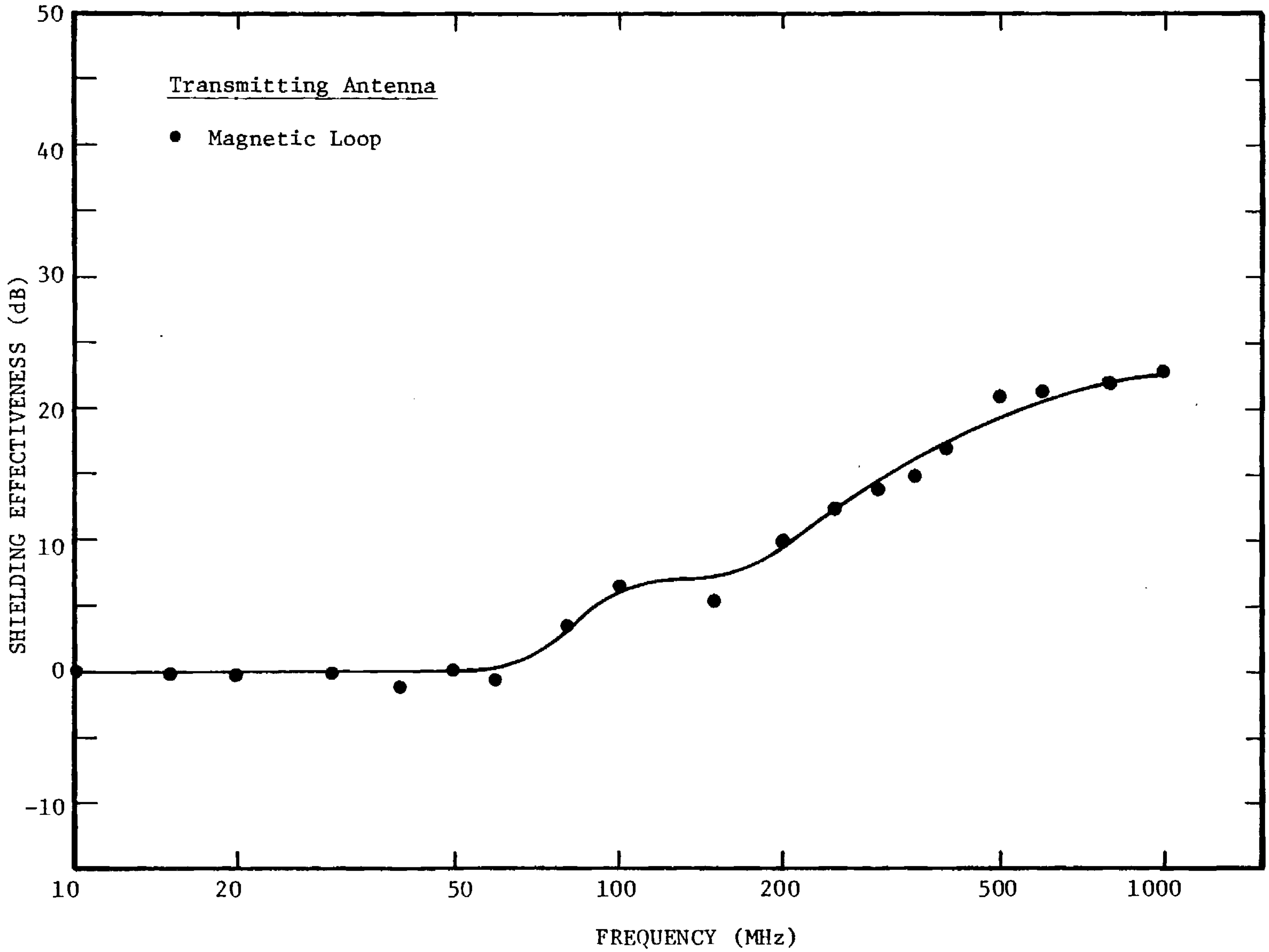


Figure 24. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 40% by Weight of Celanese GY-70 Fibers

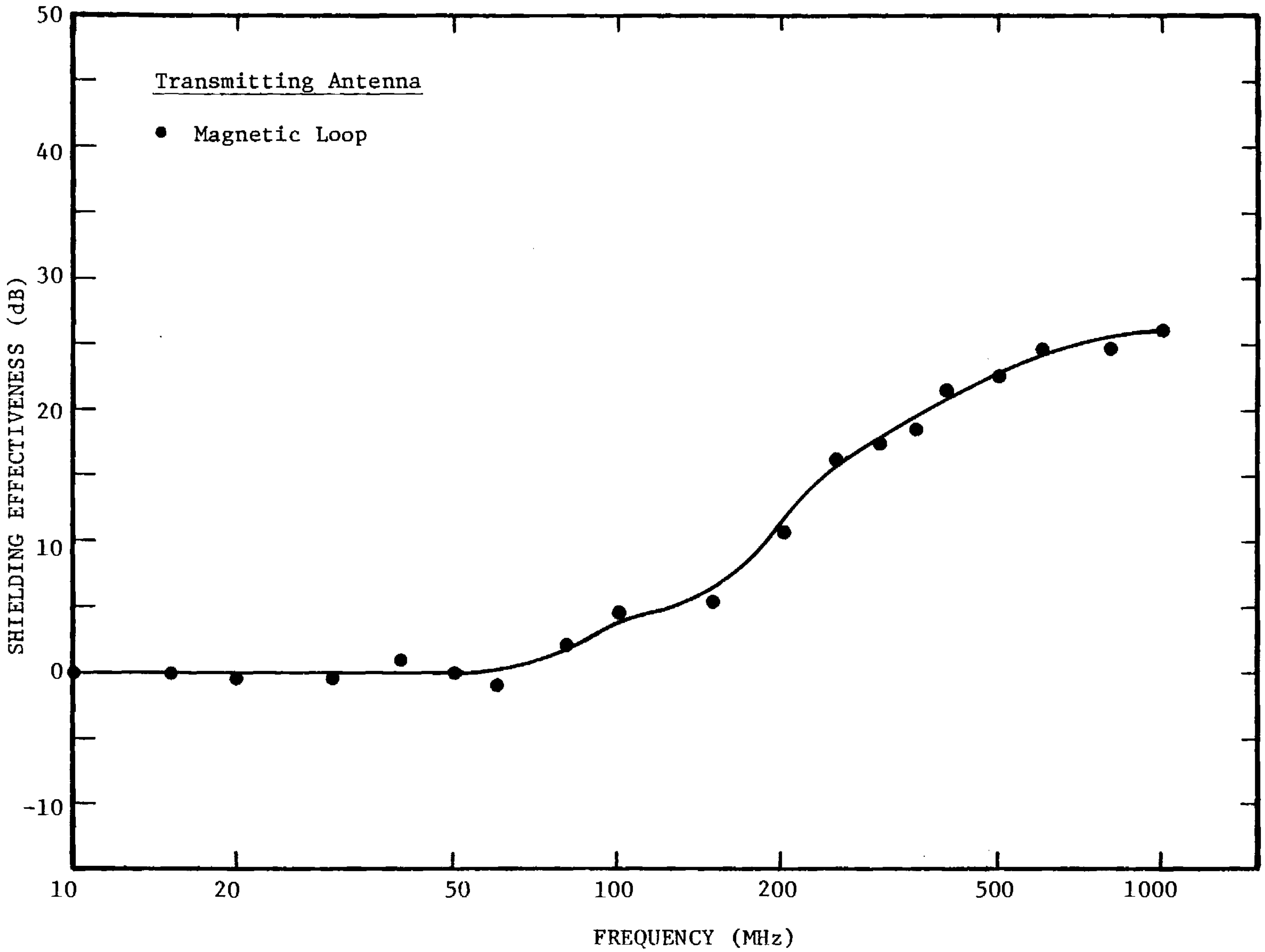


Figure 25. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 25% by Weight of Union Carbide VSB-32-T and Fibers Initially 0.5 Inch Long

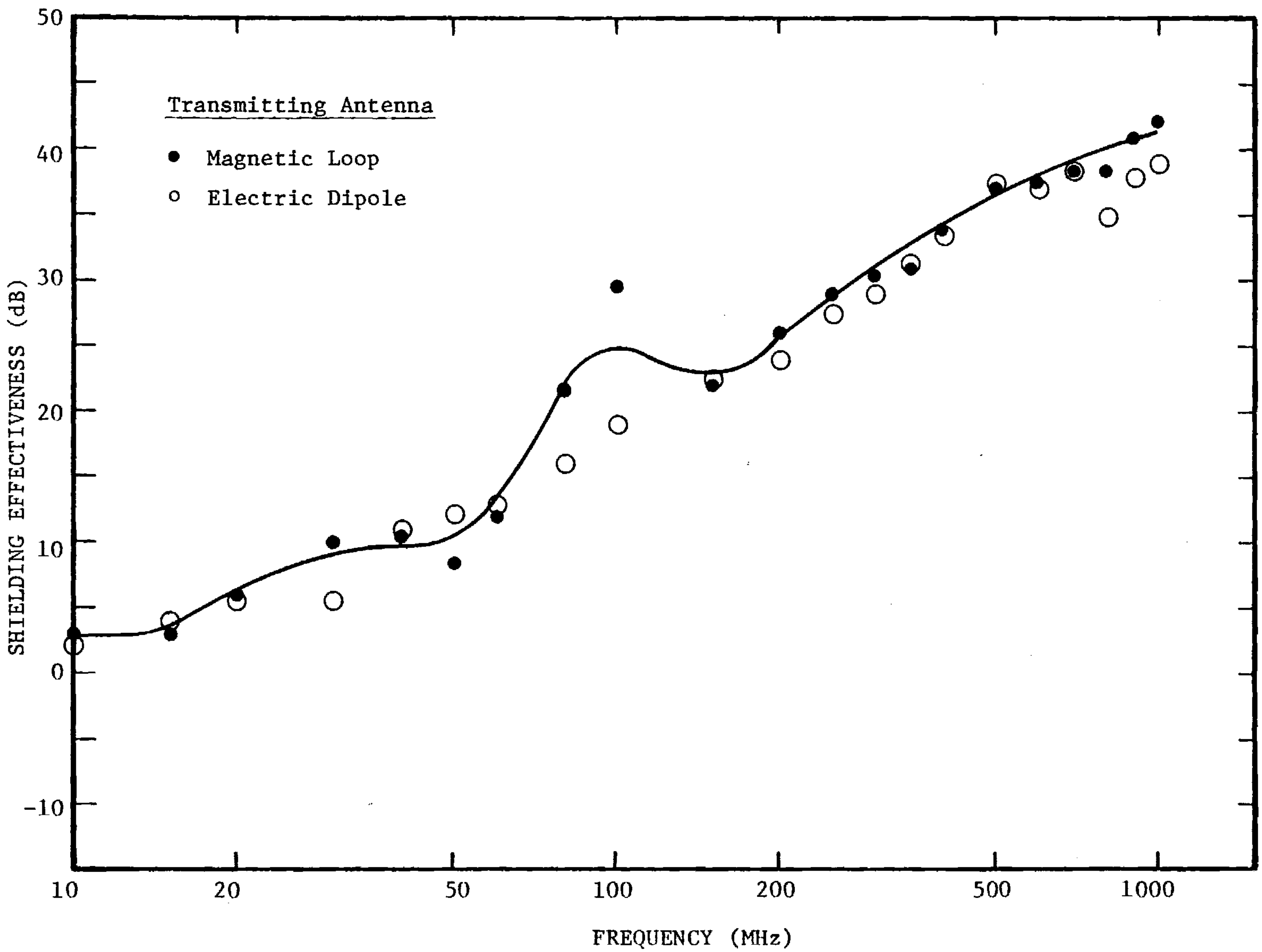


Figure 26. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 40% by Weight of Union Carbide VSB-32-T and Fibers Initially 0.5 Inch Long

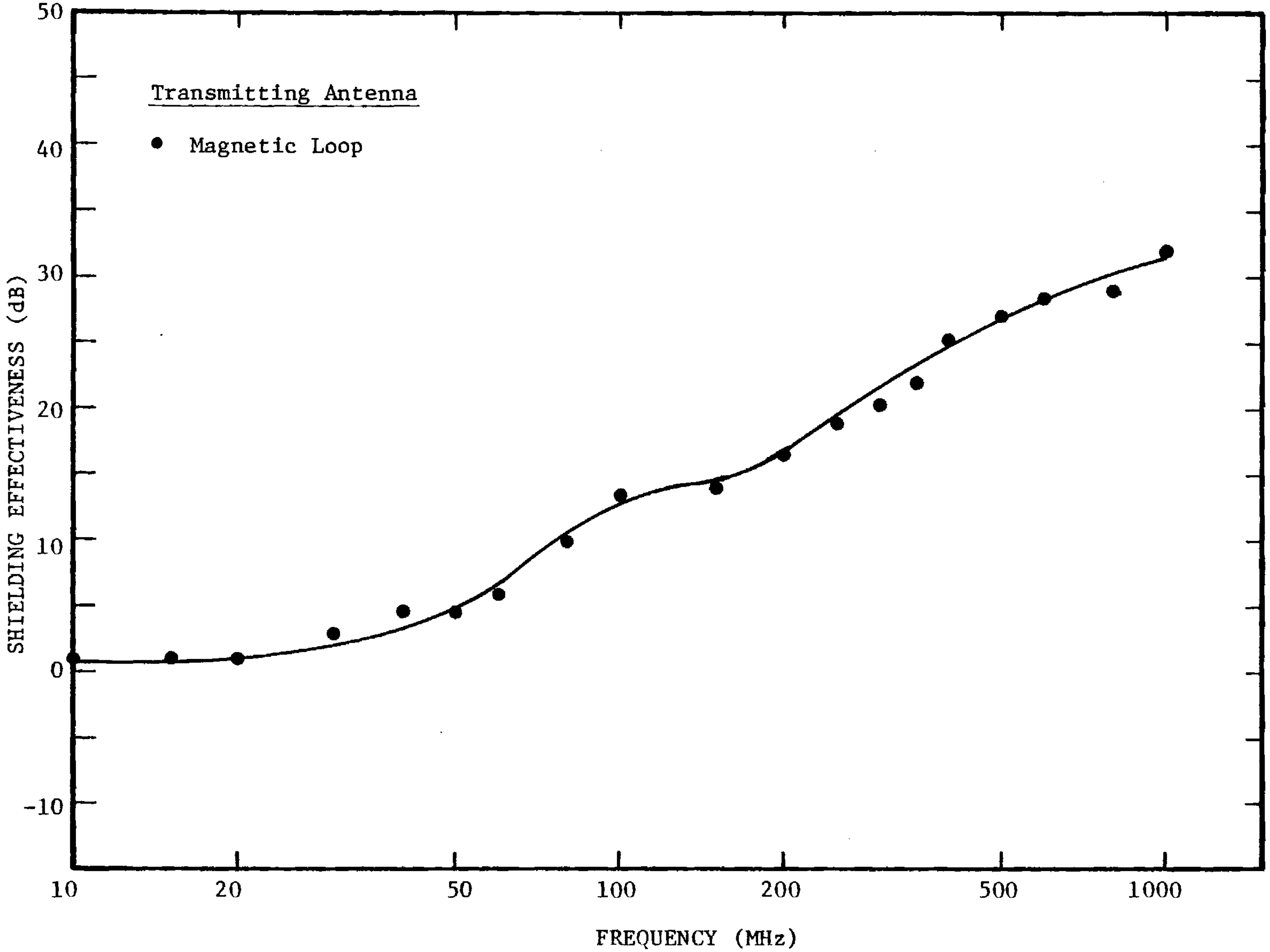


Figure 27. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 10% by Weight of Lundy RoMHOglas and 30% by Weight of Union Carbide VSB-32-T and Fibers Initially 0.5 Inch Long

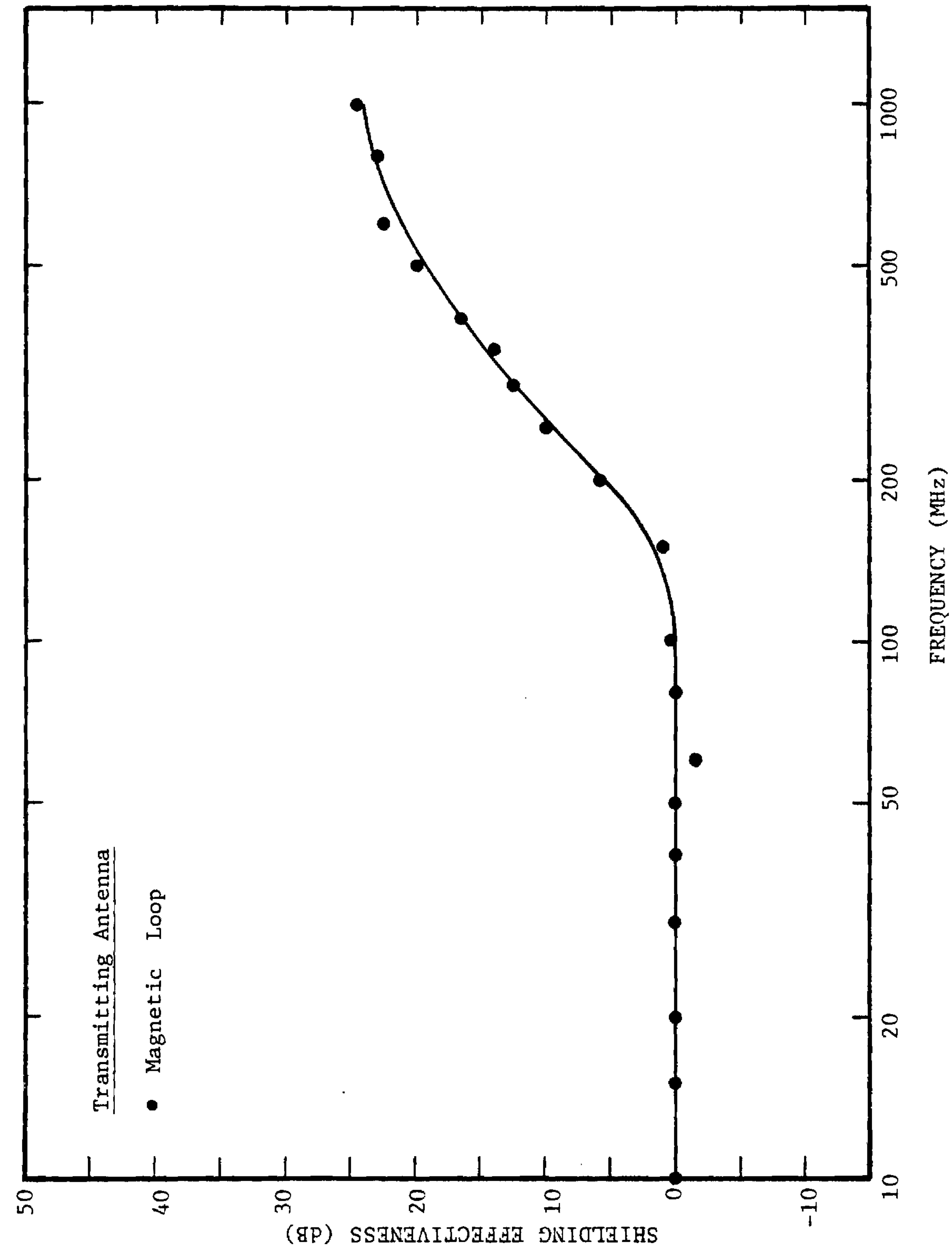


Figure 28. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate Structural Foam Plaque Filled with 20% by Weight of Lundy RoMHOglas and with 20% by Weight of Union Carbide VSB-32-T and Fibers Initially 0.5 Inch Long

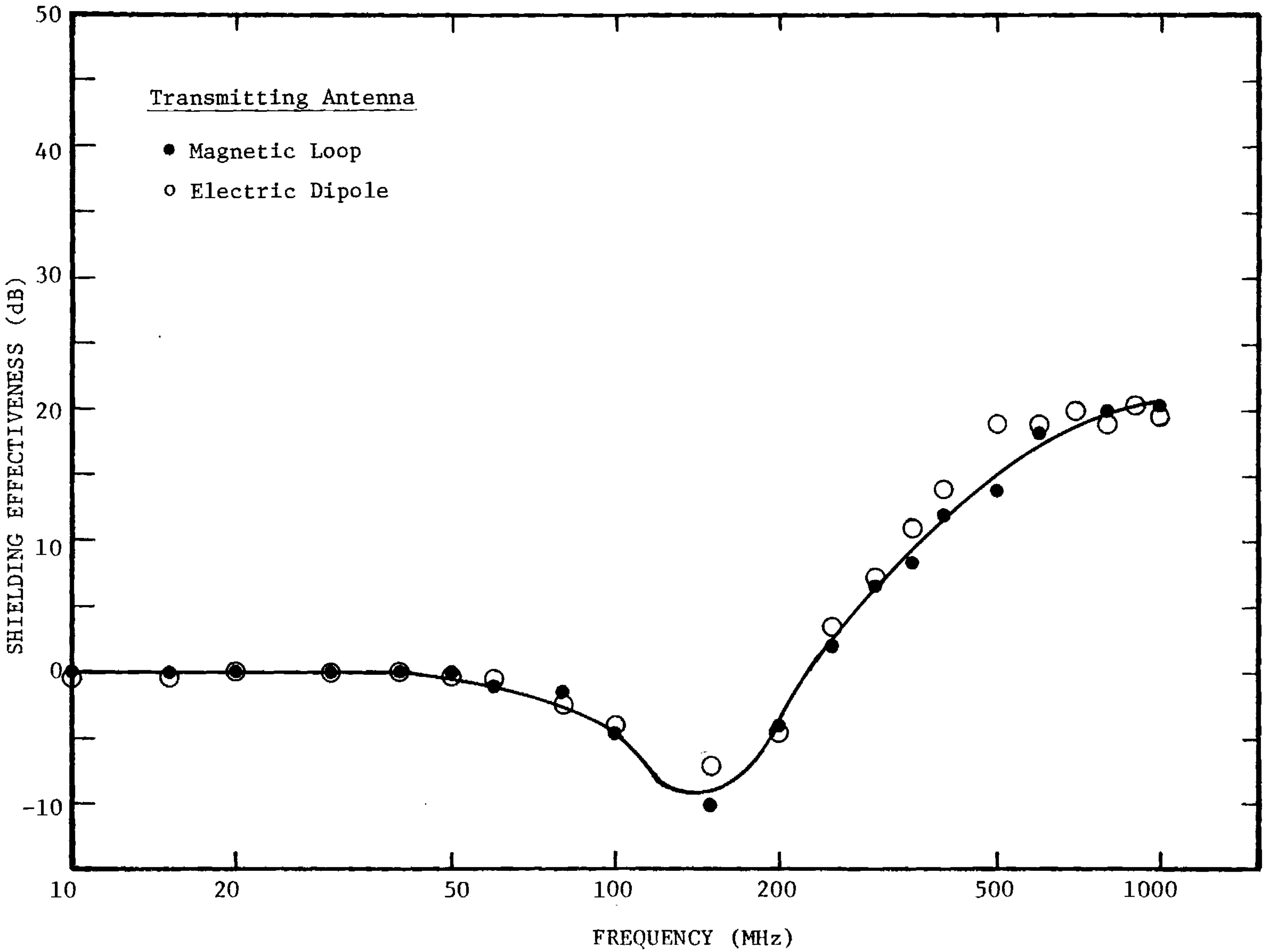


Figure 29. Measured Shielding Effectiveness of an Injection Molded, Polycarbonate, Structural Foam Plaque Filled with 30% by Weight of Lundy RoMHOglas and 10% by Weight of Union Carbide VSB-32-T and Fibers Initially 0.5 Inch Long

fibers were initially 0.5 inch long upon entering the molding machine. No shielding was observed from 10 to about 300 MHz for these samples. A negative value of SE was measured around 200-300 MHz but this is not a characteristic of the shielding properties of the material. The panel appears to be acting like a lens and focusing energy on the receiving antenna thus giving a higher transmitted signal with the panel than without. A similar effect was observed in testing some of the other panels. Only positive values of SE are physically realizable. A positive value of SE is observed above about 300-400 MHz for the Lundy material. The SE gradually rises and at 1,000 MHz the SE is 14, 16, and 20 dB for 15, 25, and 40% concentrations, respectively.

Figures 15-17 are identical to the cases shown in Figures 12-14, respectively, except that the fibers were 0.75 inch long in the former case. Little practical difference can be seen between the 0.5 and 0.75 inch fibers. It appears that the molding machine so breaks the fibers that they end up with about the same final length in the panels.

Figures 18 and 19 show the SE obtained with Union Carbide Thornel VMD at 25 and 40% concentrations, respectively. No shielding is observed up to 400 MHz. The SE then rises to 12 dB for the 25% panel and to 14 dB for the 40% panel at 1,000 MHz. VMD is a milled mat material (a fine powder). Thus, it was anticipated that VMD could not provide effective shielding since a substantial number of fiber contacts is necessary for good SE.

Figures 20-22 show the SE observed from 15, 25, and 40% by weight concentrations, respectively, of Hercules AS material. The lowest concentration shows no shielding below 200 MHz. Shielding commences at a lower frequency as the concentration of the AS material is increased with the 40% panel showing SE above 50 MHz. At 1,000 MHz the measured SE was 22, 30, and 38 dB for the 15, 25, and 40% panels, respectively. At 100 MHz the 40% panel produced only about 10 dB of SE.

Figures 23 and 24 are for Celanese GY-70 with 25 and 40% concentrations, respectively. Positive values of SE start at 200 and 70 MHz and increase to 17 and 23 dB at 1,000 MHz for the 25 and 40% panels, respectively.

Data on Union Carbide VSB-32-T material are shown in Figures 25 and 26 for 25 and 40% concentrations, respectively. The 40% panel showed 3 dB of shielding at 10 MHz, about 20 dB at 100 MHz, and 42 dB at 1,000 MHz. The 25% panel showed no shielding below 60 MHz and rose to 26 dB of SE at 1,000 MHz.

A combination of Lundy RoMHOglas and Union Carbide VSB-32-T was tested to determine if improved SE could be obtained by combining the two materials. The total filler concentration was kept constant (40% by weight) while the amount of the two fillers was varied. The measured data are presented in Figures 27-29 and show that the SE increases as the percentage of VSB-32-T is increased.

The 40% concentration of Union Carbide VSB-32-T provided the greatest shielding effectiveness of all the filler materials tested. It gave more SE over the entire 10 to 1,000 MHz range than any of the other materials tested. It also provided 10 to 25 dB of shielding in the 50 to 200 MHz range where most of the other materials provide essentially no shielding. At 40% by weight of the filler material, the following ranking of materials was obtained for their ability to provide shielding. They are listed in order from greatest to least shielding.

1. Union Carbide VSB-32-T
2. Hercules AS-4/1805
3. Celanese GY-70
4. Lundy RoMHOglas
5. Union Carbide Thornel VMD

As previously mentioned, VMD is a milled mat material and is in powder form in the panel. Thus, little shielding is expected from VMD since the conducting particles will be isolated from one another and not contacting. Lundy RoMHOglas fibers were also expected to provide little shielding since the aluminum coating oxidizes and this oxide layer tends to inhibit electrical contact between fibers. Carbon fibers, in contrast, do not have a surface oxide layer and should have better fiber to fiber contact properties. It was anticipated that the shielding would be better for carbon fibers having higher bulk electrical conductivity. It appears that high modulus pitch fibers have the highest electrical conductivity and, hence, should provide the largest shielding if these brittle fibers can be processed in such a fashion that they are not broken into very short lengths by the time they arrive in the panel.

The amount of shielding required from an enclosure depends upon the particular application for which it is intended. Hence, it is difficult to make general statements that apply to all situations. For example, shielding can be obtained by enclosing particularly susceptible components, by enclosing the entire piece of equipment, or by filters placed inside the electronic circuits. If the majority of the shielding is to be obtained from the housing for the equipment, then this housing should provide a certain minimal amount of shielding. The amount required depends heavily on the application, location, and frequency range of operation. Certainly, 10 dB of SE is not adequate while 100 dB is difficult to obtain. Military electronic equipment usually requires 60-70 dB of shielding from the housing while civilian radio frequency equipment normally requires less shielding and 30-40 dB of SE is probably typical. In contrast, shielding is not an important consideration for many consumer products.

None of the materials tested provided adequate SE for military application in the 10-1,000 MHz frequency range. All of the materials showed little or no shielding at 10 MHz and a gradual increase in SE as the frequency was increased to 1,000 MHz. Almost all samples tested provided less than 10 dB of SE below 200 MHz. Only 40% VSB-32-T, 40% AS-4/1805, and the mixture of 30% VSB-32-T and 10% RoMHOglas provided slightly more than 10 dB of SE at 200 MHz. Only 40% VSB-32-T and the 40% AS-4/1805 provided adequate SE in the UHF range for civilian application.

IV. SUMMARY AND RECOMMENDATIONS

The analysis performed during this program and which is summarized in this report was oriented toward obtaining trends in shielding effectiveness (SE) versus material parameters of structural foam internally loaded with conductive materials (SFILCM). Several analysis techniques were considered including moment method, wire grid, meteorological, and plane wave analysis.

The salient aspects of the findings assembled in this report can be summarized as follows.

1. A large number of contacting particles or fibers is required in the foam to provide significant SE.
2. The moment method is not applicable for analyzing SFILCM since it cannot handle the very large number of particles involved. However, using a periodic wire patch model for the conducting particles, the moment method provides insight into the low frequency SE of the SFILCM.
3. The wire grid model is inadequate for SFILCM analysis since it assumes that all fibers are contacting their nearest neighbors. It does, however, lend insight into the need for contacting particles to obtain SE.
4. Meteorological models are not applicable to SFILCM since they utilize non-contacting particles.
5. Plane wave analysis provides an adequate analysis tool for SE evaluation of SFILCM. The principal difficulty with this technique is associating an effective conductivity to the network of contacting fibers.
6. The dielectric constant of the structural foam does not affect the SE of SFILCM as long as its value is less than 16 and as long as the conductivity of the SFILCM is greater than 1 Siemen/meter.
7. Long thin fibers provide better SE than short fat ones.
8. To replace metal housings for radio sets in military equipment, 60 to 70 dB of SE is required from the SFILCM.
9. The conductivity of the SFILCM must be 300 to 400 Siemen/meter or greater to provide 60 dB or more of SE from 1/4 to 3/8 inch thick panels in the HF (3-30 MHz) to VHF (30-300 MHz) frequency range.

10. The highest concentration of filler always produced the best shielding. The largest concentration tested was 40% of filler by weight.
11. None of the materials tested provided adequate shielding (60-70 dB) for military application in the 10-1,000 MHz range.
12. Adequate shielding (30-40 dB) for civilian use in the UHF (300-3,000 MHz) range was obtained from a 40% concentration of Union Carbide VSB-32-T and from a 40% concentration of Hercules AS-4/1805.
13. All of the materials tested provided less than 10 dB of shielding effectiveness below 50 MHz. This is considered insufficient shielding for radio frequency application.
14. The ranking of the materials tested at 40% filler concentration from best to worst is:
    a. Union Carbide VSB-32-T
    b. Hercules AS-4/1805
    c. Celanese GY-70
    d. Lundy RoMHOglas
    e. Union Carbide Thornel VMD

As a result of the investigation on this program, the following recommendations are made for future work.

1. Improve material handling techniques to reduce fiber breakup so that fiber lengths are increased in the foamed parts.
2. Use higher modulus pitch fibers to increase the electrical conductivity of the fibers.
3. Use as high a concentration of filler material as possible that still provides acceptable mechanical properties from the part.

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